2022 Annual Meeting

Seismological Society of America Technical Sessions 19–23 April • Bellevue, Washington

The SSA 2022 Annual Meeting is its first in-person gathering since 2019 and will convene at the Hyatt Regency Bellevue, featuring more than 750 technical oral and poster presentations, plenary sessions, workshops, special interest groups and field trips.

The following schedule of events and abstracts are valid until 22 March 2022 and subject to change.

Annual Meeting Co-Chairs

The Society is grateful to the SSA 2022 Co-chairs Jackie Caplan-Auerbach, Western Washington University, and David Schmidt, University of Washington.

Contact

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Technical Program

Plenary Sessions

Keynote Address: The Cascadia Margin Revealed

Tuesday, 19 April, 5:30–6:30 PM

Suzanne Carbotte of Lamont-Doherty Earth Observatory

The keynote lecture by Suzanne Carbotte will focus on new research being conducted in Cascadia and will feature recent active source surveys of the Juan de Fuca plate and Cascadia margin and the new scientific insights that these data provide.

Science and Technology from a Makah Perspective—Incorporation of Native American Knowledge Systems

Wednesday, 20 April, 11:30 AM–12:30 PM

Janine Ledford, Executive Director of the Makah Cultural and Research Center

The Future of Subduction Zone Science

Wednesday, 20 April, 6–7 PM

Panelists: John Power, U.S. Geological Survey; Laura Wallace, GNS Science, University of Texas, Austin; S. Shawn Wei, Michigan State University. Moderated by Anne Sheehan, University of Colorado, Boulder

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Subduction zones host a range of seismic phenomena, including the world's largest earthquakes along the megathrust, in-slab and deep-focus earthquakes, shallow crustal events, tremor and volcanic seismicity. The structure and behavior of subduction systems provides insight into Earth's evolution and plate tectonic processes. A panel will present their vision for the future of subduction zone science and discuss the important next steps to expand our understanding of subduction processes.

SSA President's Address and Awards Ceremony

Thursday, 21 April, 11:30 AM–12:30 PM

SSA President Peggy Hellweg will preside over the awards ceremony and provide an update on the Society. Immediate Past President John Townend (2021-22) will deliver the presidential address. The 2021 honorees:

- William Ellsworth, Harry Fielding Reid Medal
- Seyed Mostafa Mousavi, Charles F. Richter Early Career Award
- Timothy Ahern, Frank Press Public Service Award

Joyner Lecture: A Futurist's View of Earthquake Impact Estimation

Thursday, 21 April, 6–7 PM

David J. Wald, U.S. Geological Survey

Estimating impacts due to earthquakes—whether rapidly for emerging disasters or planning for future scenarios—entails the direct interface of seismological and civil engineering expertise and tools. Both endeavors require considering uncertain models and data since the main components of loss estimation—namely shaking, exposure and vulnerabilities—entail inherent uncertainties. Since actionable response or planning requires confidence in our results, improvements in our loss calculations require continued collaboration. Fortunately, advancements in remote sensing, rapid in-situ monitoring and impact reporting, and machine learning—combined with new datasets such as global building footprints and inventories—allow for innovative data-fusion strategies that integrate with existing models and should significantly improve the accuracy and spatial resolution of rapid shaking and loss estimates. Some of the same tools and strategies are also applicable for long-term loss and risk assessments. Wald's 2021 William B. Joyner lecture will feature a combined seismological and earthquake engineering view of future earthquake response and recovery, where the initial impact estimates — as well as secondary hazards—are rapidly supplemented with crowd-sourced and remotely sensed observations that are integrated holistically for a more accurate view of the consequences.

Frontiers in Seismology

Friday, 22 April, 11:30 AM–12:30 PM

Panelists: Alice-Agnes Gabriel, University of Munich; Simon Stähler, ETH Zürich; Zhongwen Zhan, Caltech

New advances in seismological techniques and instrumentation provide opportunities to better understand earthquakes, map seismicity and refine models of the inner structure of planetary bodies. These approaches also present challenges on how to optimize instrumentation and deal with big data. In this plenary, we explore the science enabled by three emerging frontiers: distributed acoustic sensing technology, high performance computing and seismic instrumentation deployed to neighboring planets.

Special Interest Groups

SSA 2022 offers nine special interest group meetings (SIGs).

- 50-State Update of the USGS National Seismic Hazard Models Open Discussion
- Diversity, Equity and Inclusion in Seismology
- Future of Seismic Infrastructure, Invitation for Early Collaborative Efforts Both On Land and Offshore
- Ground Motion Simulation Validation (GMSV)
- Is the Southern Cascadia Region Different? Known Unknowns, Unknown Unknowns and What to Do about Them
- Latest Seismological and Geodetic Data and Results from Onshore-Offshore Southern Alaska
- Modeling of Seismic Site Amplification using AI
- Role of Seismic Networks in Monitoring Climate Change
- SOS (Save Old Seismograms)

Workshops

SSA offers workshops for members to help advance their skills.

Introduction to Machine Learning

Tuesday, 19 April, 9 AM–Noon

Instructors: Karianne Bergen, Brown University; Christopher W. Johnson, Los Alamos National Laboratory; Will Reichard-Flynn, Los Alamos National Laboratory; Youzuo Lin, Los Alamos National Laboratory

A hands-on look at how to use machine learning concepts in seismological research.

The workshop will cover introductory machine learning topics such as regression, classification, clustering, data cleaning, feature engineering and automatic feature extraction with deep learning. Attendees will then learn about the practical issues that are encountered when applying these methods to waveform and seismicity data.

Machine Learning II: Advance Your Skills

Tuesday, 19 April, 1–4 PM

Instructors: Karianne Bergen, Brown University; Christopher W. Johnson, Los Alamos National Laboratory; Will Reichard-Flynn, Los Alamos National Laboratory; Youzuo Lin, Los Alamos National Laboratory

This workshop offers attendees the chance to refine and expand their machine learning knowledge. Instructors will demonstrate more advanced techniques, and attendees will take a hands-on look at how to use them in seismological research.

Publishing: How to Review and How to Be Reviewed

Tuesday, 19 April, 1–4 PM

Instructors: Allison Bent, editor-in-chief of *Seismological Research Letters*; John Ebel, Boston College; P. Martin Mai, editor-in-chief of *Bulletin of the Seismological Society of America*

Learn how to review a scientific paper and how to respond effectively to reviews of your own work.

Field Trips

Cascadia by Canoe

Saturday, 23 April, 7 AM–10 PM

Trip Leaders: Brian Atwater, U.S. Geological Survey at University of Washington; Corina Allen, Washington Geological Survey; Diego Melgar, University of Oregon

Hardy participants will spend the day canoeing the Niawiakum River, viewing muddy signs of megathrust earthquakes. Low-tide exposures at Willapa Bay, Washington attest to great Cascadia earthquakes with remains of subsided spruce forests and sand layers from a tsunami wave train. A full-day trip with a late evening return.

First Light Kayak Tour on Lake Washington

Saturday, 23 April, 7–10:15 AM

Join experienced REI guides for a first light paddle on the tranquil waters of Lake Washington. After launching our kayaks from Enatai beach, participants will paddle along the shoreline, taking full advantage of the morning serenity. Enjoy views of the Issaquah Alps, the Cascade Mountains and on a clear day catch a glimpse of iconic Mt. Rainier basking in the light.

Seattle Geology

Saturday, 23 April, 7:30 AM–6:30 PM

Trip leaders: Ralph Haugerud, U.S. Geological Survey; Elizabeth Barnett, Shannon & Wilson; Bill Laprade, Shannon & Wilson; Elizabeth Davis, University of Washington

Seattle is subject to earthquakes on shallow faults within the crust of the North American plate, on extensional faults within the down-going Juan de Fuca slab, and on the Cascadia plate-boundary thrust fault. This trip introduces the geomorphology and stratigraphy within Seattle that record shallow faulting and determine site response to earthquakes on all sources. Participants should plan for a ~2 mile walk with 250 ft elevation gain, sandy beach, cobbly beach, rip-rap and muddy river bank.

Virtual Program

For 2022, SSA will broadcast a selection of presentations online, which can be accessed by attendees with tickets to our Virtual Meeting. The schedule was developed in consultation with the session conveners.

Please note: Some sessions in the virtual program also have presentations available only to in-person attendees.

The oral sessions scheduled in Cedar and Grand E-K will be streamed online.

SSA Meetings Code of Conduct

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive and welcoming environment for all SSA sponsored meeting participants, including attendees, staff, volunteers and vendors. All participants at SSA meetings are expected to be considerate and collaborative, communicating openly with respect for others and critiquing ideas rather than individuals. Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated.

For a detailed description of the ethics and code of conduct policies, please visit the SSA website: seismosoc.org/meetings/code-of-conduct.


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Technical Sessions

The 15 January 2022 Tonga Eruption and Tsunami

The 15 January 2022 eruption of Hunga Tonga-Hunga Ha'apai in the Tonga Islands was unprecedented in modern times. It was one of the largest volcanic explosions of the instrumental era and also caused atmospheric shockwaves that circled the globe. The eruption produced a tsunami that traveled throughout the Pacific and was also observed at locations in the Atlantic Ocean and the Mediterranean Sea. We welcome papers on the eruption, the atmospheric waves, any sources and characteristics of the tsunami, remote or nearby measurements of any of the associated phenomena, as well as threat assessment and communications and impacts.

Conveners: Peggy Hellweg, University of California, Berkeley; Lori A. Dengler, Humboldt State University; Emile A. Okal, Northwestern University; Seth Moran, U.S. Geological Survey; Stuart Weinstein, PTWC; Summer Ohlendorf, NTWC

50-State Update of the USGS National Seismic Hazard Models

The USGS National Seismic Hazard Models (NSHMs) are a bridge between best-available earthquake science and public policy. By the end of 2023, the National Seismic Hazard Model Project (NSHMP) will publish a 50-State NSHM, focusing on updates to the conterminous U.S. (last updated in 2018) and Alaska (last updated in 2007) models. The update to the Hawaii model, published in 2021, will be included as part of the 50-State NSHM update. The NSHMP has been developing and evaluating new data and models over the past year and has held a number of public workshops to present early input models to the scientific community for feedback. Planned updates for the 50-State NSHM include better representation of epistemic uncertainties, new seismicity models, updated geologic and geodetic deformation models, improved treatment of segmentation and multi-fault ruptures, NGA-Subduction GMMs, incorporation of physics-based (3D simulation) GMMs, modified location of the CEUS and WUS attenuation boundary, basin effects and site response models. In addition, the NSHMP plans to develop a research NSHM that may include directivity, non-ergodic aleatory uncertainty in GMMs and time dependence models. In early 2022, the NSHMP will hold a multi-day public workshop to present the draft model for the 50-State NSHM update.

This session will outline the next steps in finalizing the 2023 50-State NSHM and explore the implications of the draft model. NSHMs are community consensus-based models that are constantly aiming to leverage from the latest data, models and tools available at the time to evaluate and to validate hazard assessments as we undertake an updating process. We invite abstracts on implications, sensitivities and uncertainties of new sources and GMMs that are being considered for the draft model, research model, risk assessments, building code applications and other policy uses. We also invite abstracts from end users on applications and needs of NSHMs in end user products.

Conveners: Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Edward H. Field, U.S. Geological Survey (field@usgs.gov); Morgan P. Moschetti, U.S. Geological Survey (mmoschetti@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Kishor S. Jaiswal, U.S. Geological Survey (kjaiswal@usgs.gov); Sanaz Rezaeian, U.S. Geological Survey (srezaeian@usgs.gov); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov); Emel Seyhan, Risk Management Solutions, Inc. (emel.seyhan@rms.com)

Adjoint Waveform Tomography: Methods and Applications

Adjoint waveform tomography and full waveform inversion methods are providing new models of Earth structure. These methods use numerical 3D wave propagation to determine the sensitivity of waveform misfits to sub-surface structure and involve iterative inversion strategies that require complex workflows. As such, they are data and computationally intensive and benefit from recent developments in full waveform solvers and high-performance computer systems.

This session solicits presentations on adjoint waveform tomography and full waveform inversion, including contributions on theoretical and methodological developments as well as applications on reservoir, local, regional and global scales.

Conveners: Arthur J. Rodgers, Lawrence Livermore National Laboratory (rodgers7@llnl.gov); Qinya Liu, University of Toronto (qinya.liu@utoronto.ca); Michael Afanasiev, Mondaic Ltd. (michael.afanasiev@mondaic.com); Ryan Modrak, Los Alamos National Laboratory (rmodrak@lanl.gov)

Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science

Earthquake Early Warning (EEW) systems are able to provide a few to tens of seconds of warning for incoming strong ground motions after the rupture of a significant earthquake has initiated. For effective EEW, the rapid assessment of and alerting for an evolving earthquake is necessary, requiring action based on small increments of data. The 'brains' of EEW systems are constantly being improved in terms of speed and accuracy, through aspects such as updates to algorithms, the addition of novel data sources, the incorporation of additional earthquake physics and more. Increased processing capabilities also allows for more computational intensive measures to be considered.

This session invites submissions on any aspect of the development or improvement of an EEW system, which may include: algorithm development and performance review, improved detection/discrimination techniques, the use of data sources beyond traditional seismic stations, social and physical science perspectives on alerting logic, methods of reducing missed or false alerts or new approaches to EEW from around the world.

A portion of this session will also focus on the current state of practice of the ShakeAlert system with emphasis on network operations, the possible wider expansion of ShakeAlert and lessons learned from recent events (e.g. Lone Pine, Westmoreland, Antelope Valley). We also encourage abstracts related to the role of EEW in engineering and social science to assess the current status of ShakeAlert on the West Coast of North America and of EEW operations worldwide.

Conveners: Sarina C. Patel, University of California, Berkeley (sarina.patel@berkeley.edu); Stephen Crane, Natural Resources Canada (stephen.crane@nrcan-rncan.gc.ca); Fabia Terra, University of California, Berkeley (terra@berkeley.edu); Mouse Marie Reusch, Pacific Northwest Seismic Network (topo@uw.edu)

Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy

Field and remote sensing observations of recent ruptures at the Earth's surface highlight variable rupture geometries, surface slip distributions, zones of distributed or off-fault deformation and fault zone damage. The extent to which these complex and heterogenous patterns are consistent or variable between earthquakes is a fundamental question in earthquake science and remains largely unknown. Meanwhile, advances in numerical and analog modeling and laboratory experiments expand our ability to study strain accumulation and release and the landscape response through multiple earthquake cycles. Additionally, advances in geochronology allow us to better constrain earthquake timing and slip rates, enabling higher resolution comparisons of spatial and temporal patterns of slip within a fault zone. In this session, we encourage abstracts that investigate spatial and temporal patterns (including their causes and uncertainties) in strain accumulation and release spanning coseismic to geologic timescales to address questions such as: 1) How variable or consistent are patterns of surface slip and distributed deformation from one earthquake to the next and along ruptures?; 2) How do we infer geologic rates based on limited geodetic records?; 3) How does earthquake timing and recurrence cluster through space and time?; 4) Are observations from single events representative of earthquake and fault behavior over geologic timescales?; 5) How applicable are observations and findings across fault systems? We welcome contributions that present new observations or theories on the patterns and variability in earthquake rupture from field (paleoseismology, tectonic geomorphology), remote sensing (geodesy) or modeling (numerical or analog simulations or laboratory experiments) studies in any tectonic setting that will further our understanding of fault behavior over modern to geologic timescales.

Conveners: Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Chris Milliner, Caltech (milliner@caltech.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Austin Elliott, U.S. Geological Survey (ajelliott@usgs.gov); Jessica A. T. Jobe, U.S. Geological Survey (jjobe@usgs.gov)

Advances in Geophysical Sensing

Seismological studies depend on the capability to measure ground motion resulting from the passage of seismic waves. Similarly, geodetic studies of tectonic and volcanic deformation are underpinned by measurements of changes in the shape of the Earth. Advances in observational geophysics rely on improvements in the quality of measurements and innovations that extend the types and ranges of phenomena observed. These advances both drive and are driven by development of theoretical and computational approaches to interpret observations. Recent years have seen considerable efforts to improve the quality of geophysical sensing. New techniques have been developed that complement established approaches by measuring new quantities and improving the quality and density of observations. Existing sensing techniques have been improved by reducing instrument self-noise, expanding bandwidth, improving calibrations for sensitivity and drift and developing compact and rugged instruments with lower power requirements for easier operation in the field. Dense multi-element networks in a variety of settings may use arrays of inexpensive sensors developed initially for consumer electronics purposes. There are often particular challenges to operating instruments in hostile locations such as the oceans, polar regions, volcanoes, other planets or very remote sites on Earth that have spurred technical advances. Methods of removing environmental noise from observations have been critical to improving geophysical observations, particularly within the oceans, but atmospheric and hydrological noise can also be important.

This session will provide an opportunity for scientists, engineers and instrument developers to discuss recent advances in the full range of sensors and sensing techniques for seismology, geodesy and related fields and explore potential applications of emerging sensing capabilities and future scientific needs and challenges.

Conveners: William S. D. Wilcock, University of Washington (wilcock@uw.edu); Paul Bodin, University of Washington (bodin@uw.edu); Spahr C. Webb, Columbia University (scw@ldeo.columbia.edu); Erik K. Fredrickson, University of Washington (erikfred@uw.edu); Dana A. Manalang, University of Washington (manalang@uw.edu)

Advances in Geospatial Modeling of Seismic Hazards

Geospatial modeling analyzes spatial relationships and patterns of geographic features on sociocultural and physical processes. Recent developments in geospatial modeling of seismic hazards have benefited from the rapid growth of multi-source data (e.g., seismic waveform, remote sensing images, GPS time series) and advances in modeling techniques (e.g., machine learning and deep learning). These have opened up the possibility of performing seismic hazard assessment at different phases, such as pre-earthquake planning and post-earthquake reconnaissance. In addition, the spatial distribution pattern of different types of geographic features on seismic hazards and its temporal variation provide the possibility of investigating the driving mechanism of seismic hazards. We welcome contributions of recent advances in and applications of geospatial modeling on various types of seismic hazards (e.g., shaking, landslide, liquefaction), including (but not limited to) geospatial data collection, processing and management, data mining, artificial intelligence in geospatial modeling and spatiotemporal analysis.

Conveners: Weiwei Zhan, Tufts University (weiwei.zhan@tufts.edu); Xuanmei Fan, Chengdu University of Technology (fanxuanmei@gmail.com); Laurie G. Baise, Tufts University (laurie.baise@tufts.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin.zhu@gfz-potsdam.de)

Advances in Seismoacoustic Methods for Explosion Monitoring

National and global security are ongoing missions whose needs are supported significantly through seismoacoustic research and development. In particular, seismic and acoustic research relevant to the detection and description of explosions—their source properties, coupling, explosive yield, phase generation and ground and atmospheric wavefield propagation – is critically important to the ability to discern anthropogenic explosion activity and assess its importance to the monitoring effort. We invite contributions relevant to the challenging field of seismoacoustic explosion monitoring, with a special focus on smaller sources, noise mitigation strategies, machine learning and deep learning applications, cloud computing, laboratory to local to teleseismic scale analyses and observations and new approaches to models and model validation.

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Delaine Reiter, Applied Research Associates (dreiter@ara.com); Sean Ford, Lawrence Livermore National Laboratory (ford17@llnl.gov); Keith Koper, University of Utah (koper@seis.utah.edu); Fransiska K. Dannemann, Sandia National Laboratories (fkdanne@sandia.gov); Michelle E. Scalise, Nevada National Security Site (scalisme@nv.doe.gov)

Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes

Recent advances in instrumentation technology have enabled scientists to deploy progressively denser networks of seismo-acoustic sensors for longer periods of time at locations closer to volcanic systems than was previously possible. Recordings from these networks have enabled researchers to glean new insights into surface and sub-surface processes that produce seismo-acoustic signals at volcanoes, insights that hold promise for improved monitoring and real-time hazard assessment. Furthermore, advances in data processing and the development of new techniques enable both new discoveries in legacy datasets and the promise of new monitoring tools. We invite submissions to this session that describe novel studies at volcanic systems involving seismic and/or infrasonic instrumentation, with particular emphasis on results that would be applicable to the monitoring and understanding of Cascade Range volcanoes.

Conveners: Weston Thelen, U.S. Geological Survey (wthelen@usgs.gov); Amanda Thomas, University of Oregon (amthomas@uoregon.edu); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); Barrett Johnson, University of Washington (bnjo@uw.edu); Seth Moran, U.S. Geological Survey (smoran@usgs.gov)

Advancing Multi-scale Evaluations of Seismic Attenuation

Understanding and quantifying seismic attenuation is key to advancing seismic hazard assessments at different spatial scales. At regional scales, the seismic quality factor Q captures path attenuation with consideration of the different wave phases (e.g., P-wave or S-wave) and attenuation mechanisms (e.g., anelasticity and/or scattering). At local scales (e.g., at a given site of interest), the empirical high-frequency spectral decay parameter kappa and its site-specific component characterize the near-surface attenuation. However, the description of seismic wave propagation is not easy especially when it comes to amplitudes. The crust and especially the shallower layers can be very variable leading to wave focusing effects or wave conversions. Furthermore, seismic source phenomena, local site amplifications or the responses of the recording instrument itself can hinder the identification of attenuation. All these reasons in connection with different measurement techniques makes it difficult to identify a unique parameter that captures seismic attenuation mechanisms at multiple scales.

This session aims to gather recent advances in physics-based or empirical modeling related to the quantification of seismic attenuation. We welcome studies focused on, but not limited to: 1) the variability and uncertainty associated with seismic attenuation measurements (e.g., the errors associated with in-situ measurements of Q, the computation bias in kappa and potential tradeoffs between kappa and source); 2) the physics-based explanation behind seismic attenuation parameters (e.g., identification of scattering versus intrinsic attenuation contributions); 3) the link among different attenuation parameters (such as kappa, Q and material damping ratio; scattering and intrinsic attenuation) at various scales and 4) challenges associated with their integration into ground motion modeling, seismic hazard assessments and site response analysis.

Conveners: Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Annabel Haendel, GFZ Potsdam (ahaendel@gfz-potsdam.de); Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Fabrice Cotton, GFZ Potsdam (fcotton@gfz-potsdam.de)

Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone

The Gorda region of the Cascadia subduction zone (CSZ) extends from the Mendocino triple junction to Southern Oregon. It is one of the most seismically active regions of the contiguous 48 states. This region is marked by two transitions: 1) that from the strike-slip tectonics of the San Andreas transform system to the CSZ and 2) that from the seismically active deformation zone associated with the Gorda plate to the relatively intact Juan de Fuca plate.

We welcome presentations addressing the tectonics in the Southern Cascadia region, as well as discussion of the tsunami, ground shaking and fault rupture hazards from the region's seismicity. We also encourage contributions on the major uncertainties in estimating risk and how new technologies may contribute to a better understanding of the area.

Conveners: Jason R. Patton, California Geological Survey (jason.patton@humboldt.edu); Lori A. Dengler, Humboldt State University (lori.dengler@humboldt.edu); Peggy Hellweg, University of California, Berkeley (peggy@seismo.berkeley.edu); Bob McPherson, Humboldt State University (robert.mcpherson@humboldt.edu); Rick I. Wilson, California Geological Survey (rick.wilson@conservation.ca.gov)

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances

Geothermal energy is an emerging renewable energy source and as a green and sustainable energy can make a significant contribution to the current worldwide challenge to reduce the net atmospheric emissions of greenhouse gases to zero (zero-net emissions target). Geothermal heat extracted from depth in excess of 400m is defined as deep geothermal energy. Enhanced Geothermal Systems (EGS) employ hydraulic fracturing to increase the rock permeability and favor a more efficient exploitation of deep geothermal reservoirs when local geology does not favor natural pathways for fluid circulation. Induced micro-earthquakes in EGS are not therefore undesired by-products but a necessary tool to create effective pathways for fluid migration and heat exchange. Thus, to develop EGS, adaptive, data-driven real-time monitoring and risk analysis of potential seismicity triggered by EGS operations are crucial for assessing the geothermal stimulation effects and demonstrating that safe and sustainable development of deep geothermal energy projects is possible. A current research-oriented EGS laboratory is being developed at the FORGE (Frontier Observatory for Research in Geothermal Energy) geothermal site in Utah, USA. We encourage contributions from FORGE and other EGS projects and field test sites that focus on geophysical technologies applied to geothermal energy, such as real-time monitoring and characterization of induced seismicity, distributed acoustic sensing, large-N array, active surface seismic, vertical seismic profiling, seismic imaging of faults and fracture zones, laboratory experiments and novel instrumentation. We also welcome submission of abstracts on modeling studies at all scales, seismicity forecasting models, hazard and risk analysis studies as well as presentations dealing with good-practice guidelines and risk assessment procedures that would help in reducing commercial costs and enhancing the safety of future geothermal projects.

Conveners: Federica Lanza, Swiss Seismological Service, ETH Zurich (federica.lanza@sed.ethz.ch); Kristine L. Pankow, University of Utah Seismograph Stations (kris.pankow@utah.edu); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Stefan Wiemer, Swiss Seismological Service, ETH Zurich (stefan.wiemer@sed.ethz.ch); Antonio Pio Rinaldi, Swiss Seismological Service, ETH Zurich (antoniopio.rinaldi@sed.ethz.ch); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov)

Development, Enhancement and Validation of Seismic Velocity Models

3D velocity and anelastic attenuation models are critical to generate useful ground motion estimates as well as many other applications. Community Velocity Models (CVMs) have been developed for these purposes in different regions. However, the potential for these CVMs to contribute to new advances in seismic hazard analysis depends on their accuracy, flexibility (e.g., meshing capabilities) and accessibility (e.g., software, efficiency).

We solicit submissions describing the development, enhancement and validation of seismic velocity and anelastic attenuation models. Among other topics, we are interested in: 1) uncertainty estimation of the velocity models as well as the resulting ground motion predictions; 2) studies on techniques for including variable-resolution features, surface topography, small-scale heterogeneities and (frequency-dependent) anelastic attenuation; 3) procedures for including multi-scale features such as fault damage zones, near-surface weathering layers, geotechnical information and other geophysical and geological data and 4) case studies for validating existing or new enhancements, for example through 3D waveform tomography, to CVMs.

Conveners: Kim Olsen, San Diego State University (kbolsen@mail.sdsu.edu); Evan T. Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Andreas Plesch, Harvard University (andreas_plesch@harvard.edu); William J. Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Distributed Deformation from Surface Fault Rupture

Distributed deformation or secondary surface fault rupture are a concern for many projects that lie within some distance of principal active faults. Attempts to model the probability of distributed ruptures and amounts of distributed deformations have considered style of faulting, fault geometry, distance from the principal fault, geologic and tectonic structural setting and whether the distributed deformations are geometrically connected to principal ruptures or dynamically triggered. Attempts to understand the causes and mechanisms of distributed fault rupture deformations have application not only to hazard assessment of engineered structures and hazard policy but also to our understanding of the shallow slip deficit, particulate vs. rock mechanics and earthquake rupture forecasting. This session invites speakers to present recent research on distributed deformations associated with surface fault rupture and participate in a broad discussion on how to understand, study and manage these deformations.

Conveners: Robb Moss, California Polytechnic State University (rmoss@calpoly.edu); Steve Thompson, Lettis Consultants Inc. (thompson@lettisci.com); Chris Milliner, Caltech (milliner@caltech.edu)

Diversity, Equity and Inclusion in Seismology

Geosciences is one of the least diverse fields and will remain so if actions are not taken to address issues of racism, sexism, homophobia and inaccessibility. In this session, we welcome participants to present on efforts undertaken to improve the diversity, equity, and inclusion of seismology, geodesy and the broader geoscience community.

We particularly encourage contributions that will include specific issues, for example: best practices for partnerships with indigenous communities, workforce development including the recruitment and retention of individuals from underrepresented groups or issues related to field safety for underrepresented individuals. Recent developments to diversify, retain and provide career development for student and early career scientists in seismology, geodesy and the broader geoscience community will be highlighted.

Conveners: Anika Knight, UNAVCO (anika.knight@unavco.org); Mo Holt, University of Illinois Chicago (mmholt@uic.edu); Kevin Kwong, University of Washington (kbkwong@uw.edu); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

Earthquake Source Processes at Various Scales: Theory and Observations

The recurrence time, ground motion and the spatiotemporal evolution of natural, anthropogenic-induced and laboratory earthquakes are strongly influenced by processes that involve the frictional and mechanical properties of the fault systems, as well as the regional and local stress field where these events nucleate. Understanding and characterizing static and dynamic earthquake source parameters is crucial for improving hazard assessment and earthquake forecasts. Similarly, understanding the various scaling relationships of these parameters and their interactions between seismic and aseismic slip modes is important for further advancing hazard estimates. This session focuses on highlighting forefront studies that aim to improve understanding of earthquake source processes and its related complexities. From theory and numerical modeling to large-scale observations at different tectonic regimes, we encourage contributions on research that explore earthquake source physics in a broad range of magnitudes and time scales.

Conveners: Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Valerie Sahakian, University of Oregon (vjs@uoregon.edu); William Ellsworth, Stanford University (wellsworth@stanford.edu); Taka'aki Taira, University of California, Berkeley (taira@berkeley.edu)

Earthquakes in the Urban Environment

The relentless urbanization and associated concentration of people and infrastructure in earthquake-prone environments brings increased focus on the local to site-specific assessment of seismic risk. Seismic hazard and risk in urban areas need to be addressed by considering all the elements that can affect the intensity of shaking and distribution of losses, considering close proximity to even moderate events and the multi-event degradation of structures. Seismic measurements in urban areas can be difficult due to abundant ambient noise, scattered energy from built structures and foundations and modified near-surface conditions. Array studies also can be difficult due to limited space and access issues. In this session, we invite presentations on earthquake studies using data processing, empirical, analytical or numerical models, which integrate urban aspects into the research of seismic hazard and risk. Topics could include studies on the source parameters of shallow earthquakes, nearby induced seismicity, attenuation in the near-field, approaches to model and mitigate dynamic seismic hazards and risks, wave propagation in a complex urban environment, ground motion spatial variability, 2D versus 3D site responses and site-city or soil-structure interactions. We also encourage presentations on recent instrumental and data processing developments in urban environments (e.g., optical fiber technology, low-cost sensors, rotation, N-arrays), along with studies on dynamic urban exposure, dealing with seismic structural health monitoring, rapid loss assessment and/or early warning systems. Similarly, we hope to include recent and innovative developments on proxies for predicting the consequences of seismic ground motion and improving the spatial distribution forecasting of earthquake losses on cities.

Conveners: Fabian Bonilla, Université Gustave Eiffel (luis-fabian.bonilla-hidalgo@univ-eiffel.fr); Philippe Guéguen, ISTerre, Université Grenoble Alpes (philippe.gueguen@univ-grenoble-alpes.fr); Stefano Parolai, Istituto Nazionale de Oceanografia e de Geofisica Sperimentale (sparolai@inogs.it); Thomas Pratt, U.S. Geological Survey (tpratt@usgs.gov); Chiara Smerzini, Politecnico di Milano (chiara.smerzini@polimi.it)

The Effects of Sedimentary Basins on Earthquake Ground Motions

The manifestation of ground shaking intensities at the surface of sedimentary basins during an earthquake is a complex phenomenon that is depends on a variety of factors, which include basin structure (shape and depth), depositional history (e.g., sediment type and layering) and characteristics of the seismic event (e.g., magnitude, directivity and azimuth). Sedimentary basins also underlie many urban settings where the potential for the amplification of strong ground motions, especially at long periods, may lead to a substantially elevated risk profile for the residing population and the built environment. As the number of long-period large-scale structures increases worldwide, estimation and realistic modeling of long-period ground motions become important considerations in seismic design. However, there is still a lack of simple guidelines for the selection of strong ground motion recordings containing surface waves and for considering their complex characteristics (such as dispersion) in engineering analysis procedures.

In this session, we seek contributions that will elucidate the impact of sedimentary basins on ground motions and the associated seismic hazards. Example topics of interest/areas of study include advances in characterizing basin structure, improving Earth models at multiple scales, performing high-fidelity 3D numerical simulations to investigate basin site response, identifying basin effects on ground motions and incorporating representative features into ground motion models. We also encourage presentations related to modeling long-period surface-wave propagation within basins, rotational motions (i.e., rocking and torsion), long-duration excitation and relevant risk to long-period structures.

Conveners: Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov); Kristel Meza Fajardo, Bureau de Recherches Géologiques et Minières (k.mezafajardo@brgm.fr); Sean K. Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Patricia Persaud, Louisiana State University (ppersaud@lsu.edu); Chukwuebuka C. Nweke, University of Southern California (chukwueb@usc.edu); Jean-François Semblat, École Nationale Supérieure de Techniques Avancées (jean-francois.semblat@ensta-paris.fr); Fernando López-Caballero, Ecole Centrale Paris, CentraleSupélec (fernando.lopez-caballero@centralesupelec.fr)

Everything Old Is New Again—Resurging Use of Analog Data

Efforts to understand Earth dynamics often depend on our ability to interpret past behaviors of complex systems. Much of this observational data was collected during the pre-digital era and is difficult to discover and access. The seismological community benefits greatly from these continuous observations that have been collected, at some locations, for over a century. When subject to analysis using modern methods, analog seismic data can reveal new insights and have the potential to enable discoveries in many fields. These include not only seismotectonics and seismic hazard, but also Earth structure, induced seismicity, ambient noise, tsunamis, landslides, volcanoes and effects associated with climate change. This data set is being rediscovered and progress continues many fronts in advancing its use.

To that end, we invite presentations from a wide range of activities that advance the preservation and discovery and illustrate the value of legacy seismic data. We seek presentations from users and maintainers of data on addressing issues concerning preservation and access as well as efforts to create standards to enhance search and discovery, improve usability and enable access. Presentations on new and successfully adapted and applied techniques demonstrating the utility of these data are strongly encouraged. Contributions may include but are not limited to, studies of seismicity, natural hazards, seismotectonics, Earth structure and climate signatures as well as studies that advance the preservation of records through scanning and vectorization and efforts towards understanding and establishing metadata standards needed to successfully use legacy data.

Conveners: Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Peggy Hellweg, University of California, Berkeley (peggy@seismo.berkeley.edu); Richard D. Lewis, Defense Threat Reduction Agency (richard.d.lewis1.civ@mail.mil); Qi Ou, University of Oxford (qi.ou@earth.ox.ac.uk)

Exploring Earthquake Source Dynamics and Wave Propagation Properties in Tectonic and Lab Environments

Current, challenging research issues include complex earthquake rupturing and the impact of physical state of media on wave propagation. Therefore, this session will cover recent advancements in the understanding of dynamics in both complex tectonic and controlled lab environments. Our understanding of earthquake source physics remains restricted due to the scarcity of documented seismic rupture along complex fault systems, which makes short-term and long-term forecasting difficult. The two most crucial concepts to understand are rupturing processes and modification waves passing through heterogeneous media. Laboratory experiments exploring real tectonic scenarios might be a feasible way for understanding and comparing earthquake source physics. Using shear rock experiments as an earthquake analogue coupled with a state-of-the-art high frequency acoustic monitoring system, various researchers have demonstrated in the past that accelerations recorded in the kilohertz range on centimeter-sized samples were self-similar to those expected at the kilometric scale for a large earthquake. Recent advances in laboratory imaging of spontaneous dynamic ruptures have allowed us to visualize and quantify stress reduction at the free surface, and its impact on friction for fault-slip histories that are similar to natural thrust and normal earthquakes. Therefore, we are open to an extensive variety of seismological studies such as moment tensor analysis, seismic tomography, frictional parameters, fault dimension assessment, fault geometry, wave attenuation characteristics, etc.

Conveners: Rohtash Kumar, Banaras Hindu University (rohtash21@bhu.ac.in); Subhash C. Gupta, Indian Institute of Technology, Roorkee (s.gupta@eq.iitr.ac.in); Ranjit Das, University Catolica Del Norte (ranjit.das@ucn.cl); Prithvi Thakur, University of Michigan (prith@umich.edu)

Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere

The InSight mission landed on Mars on 26 November 2018 and was the first to place an ultra-sensitive broadband seismometer on the surface of another planet. The mission has now reached the milestone of 1000 sols on Mars, and the Marsquake Service is frequently reporting new marsquakes. Researchers from the InSight team are making new observations and inferences regarding the structure of Mars' core, upper mantle and crust and other recent work.

Meanwhile, on the Moon, new work is happening or being planned. The Farside Seismic Suite, a NASA mission to Schrödinger Crater, was selected for flight in the mid-2020s. The Lunar Geophysical Network is in formulation for NASA's New Frontiers 5 Announcement of Opportunity and would place four geophysical stations around the Moon. Other space agencies are also interested in deploying instruments to determine the structure of the Moon. Chang'e 4 uses ground-penetrating radar to learn more about the shallow structure of the farside of the Moon. Other potential seismic targets include Venus, where researchers are beginning to consider studying venusquakes with infrasound, and icy ocean moons, where seismometers could be deployed to study icequakes and even the rocky interior.

We invite contributions on any aspect of planetary seismology. Contributions from Mars, the Moon, Venus, Mercury, icy moons, the Sun, comets, asteroids and even stars or exoplanets are all welcome. We're interested in data-driven or theoretical work, and we would also love to hear about new mission proposals, instruments and concepts.

Conveners: Ceri Nunn, Jet Propulsion Laboratory, Caltech (ceri.nunn@jpl.nasa.gov); Angela G. Marusiak, Jet Propulsion Laboratory, Caltech (angela.g.marusiak@jpl.nasa.gov); Aisha Khatib, University of Maryland (akhatib1@umd.edu)

Fault Damage Zones: What We Know and Do Not

Fault damage zones accommodate the bulk of the inelastic deformation produced during earthquakes, modify the long-term properties of the shallow crust and increase local seismic hazard through enhanced shaking. Because of their relevance to the earthquake energy balance problem, their influence on ground motions and their impact on fluid pathways near faults, damage zones have garnered the interest of a broad disciplinary range of geoscientists. Over the past two decades, increasing resolution and availability of observations, together with improvements in numerical modeling capabilities, have advanced our understanding of the spatial extent, physical (mechanical) properties and long-term evolution of damage zones. Though the understanding of fault damage zones is improving there remain many unanswered questions such as the mechanism and role of fault healing, the importance of lithology, the effect of fault maturity and the bulk damage zone rheology over time.

In this session, we welcome recent advances in the quantitative understanding of damage zones from observations, numerical models and laboratory studies. We are particularly interested in studies spanning the complete earthquake cycle, experimental studies and work bridging observations from various methods. As part of pushing our understanding of damage zones forward, we invite contributors to identify the outstanding questions in their research and potential directions that will address them, especially those requiring a collaborative, cross-disciplinary approach.

Conveners: Alba M. Rodriguez Padilla, University of California, Davis (arodriguezpadilla@ucdavis.edu); Travis Alongi, University of California, Santa Cruz (talongi@ucsc.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Thomas Mitchell, University College London (tom.mitchell@ucl.ac.uk)

Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors

Distributed Acoustic Sensing (DAS) is rapidly becoming a popular tool for seismological research, contributing to a new understanding of earth structure and its influence on wave propagation and seismic source mechanisms. DAS is enabling Large-N array seismology in novel and unique spaces. Examples of recent deployments have explored microseismicity in enhanced geothermal systems (EGS), regional scale earthquakes, the near-field source physics of underground explosions, ocean wave propagation and acoustics, glacier surface and basal processes, near-surface structure in urban areas and mass movements including landslides and avalanches. The main advantages of DAS for seismology include, but are not limited to, dense recording, wide spatial extent of virtual sensors, time-lapse repeatability and the unique opportunity to leverage existing fiber infrastructure in the form of telecommunication cables ("dark fiber"). Researchers are rapidly expanding the range of DAS applications, techniques and analysis methods. Because DAS measurements are a single-component projection of the strain (or strain-rate) wavefield along the direction of the fiber, there is a need to develop a fundamental theoretical framework to cope with this new measurement. Methods have been proposed for relating DAS measurements to traditional seismic recordings using geophones and seismometers, however much work remains in translating and matching both the phase and amplitude information between the instruments. The high spatial resolution and broadband nature of DAS furthermore allows for new data analysis methods or the adaptation of existing Large-N methods to strain recording. Large data volumes generated with DAS are also amenable to the application of machine learning for addressing data management, processing and interpretation challenges. Additionally, DAS measurements can be paired with complementary optical based measurements (i.e. distributed temperature or strain sensing), thereby gaining unique subsurface and process understanding.

We invite contributions from research related to all aspects of fiber-optic sensing methods in seismology and geophysics, including but not limited to: advancements in optical engineering; developments in theoretical and methodological aspects of fiber-optic sensing; novel processing and data handling approaches; case studies from recent and ongoing fiber-optic sensing experiments; comparisons between non-inertial and inertial instruments and insights gained from fiber-optic sensing measurements in the context of other types of seismological/geophysical datasets.

Conveners: Verónica Rodríguez Tribaldos, Lawrence Berkeley National Laboratory (vrodrigueztribaldos@lbl.gov); Kirsten Chojnicki, Pacific Northwest National Laboratory (kirsten.chojnicki@pnnl.gov); Ariel Lellouch, Tel Aviv University (ariellel@mail.tau.ac.il); Hunter A. Knox, Pacific Northwest National Laboratory (hunter.knox@pnnl.gov); Patrick Paitz, ETH Zurich (patrick.paitz@erdw.ethz.ch); Brad Lipovsky, University of Washington (bpl7@uw.edu); Herb Wang, University of Wisconsin (hfwang@wisc.edu)

From Desktops to HPC & Cloud: Emerging Strategies in Large-Scale Geophysical Data Analysis

As the availability of geophysical data continues to grow in volume and variety, many aspects of research data collection, access and processing are evolving to allow full use of large data sets. Processing large data volumes is not unique to geophysics and there exist many modern, open source languages (e.g. Python, Julia), data containers (e.g. HDF5, Zarr) and computational frameworks (e.g. Apache Spark, xarray and Dask, Ray), that can be leveraged and allow researchers to focus more on the domain-specific issues. Access to computational resources, such as HPC and cloud computing, continue to become more accessible and affordable. Specialized hardware, such as GPUs, are increasingly available in both academic and commercial computing environments and make efforts such as large scale waveform template matching possible. New computing models, like serverless architectures and Kubernetes container orchestration, expand the ways in which research can be performed. The combination of available software and computational resources increase accessibility to a new scale of inquiry, making large-scale research in seismology, infrasound, geodesy and geophysics in general more tractable than ever before. In this session, we invite researchers, data producers and data providers to share work in data-hungry applications, approaches to large data collection, storage and access and experiences with processing platforms and architectures.

Conveners: Chad Trabant, Incorporated Research Institutions for Seismology (chad.trabant@iris.edu); Jonathan K. MacCarthy, Los Alamos National Laboratory (jkmacc@lanl.gov)

Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions

Over the last several decades, the subduction zone science community has accumulated a wealth of geophysical and geological data on earthquakes and tsunamis. This has enabled the creation of more realistic and diverse numerical models of earthquake and tsunami hazards. However, critical questions about earthquake rupture characteristics, tsunami inundation extents, paleoseismic proxies and more remain unresolved. In this session we solicit presentations on recent advances in modeling earthquake rupture scenarios with particular focus on the use of iterative modeling across coseismic deformation and resultant tsunami inundation. Modeling studies incorporating real-time, historic or reconstructed data constraints (geophysical and/or geological) are expressly welcome.

In this session we hope to highlight advances in the field of earthquake and tsunami science and outline the steps needed to move towards more integrated models and filling important knowledge gaps. Such gaps may include limited geologic and/or geophysical data constraints, needs for improved modeling methodology, etc. We hope participants view this session as a community discussion on continued improvement of earthquake and tsunami science.

Conveners: Andrea D. Hawkes, University of North Carolina Wilmington (hawkesa@uncw.edu); Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Lydia M. Staisch, U.S. Geological Survey (lstaisch@usgs.gov); SeanPaul La Selle, U.S. Geological Survey (slaselle@usgs.gov); Jason S. Padgett, University of Rhode Island (jason_padgett@uri.edu)

Frontiers in Marine Seismology

Understanding of geohazards and Earth structure continues to be advanced with the development and use of marine technologies and new analysis techniques. Whether investigating the formation and evolution of structures in ocean basins, refining the controls on and potential impact of megathrust earthquake slip behavior along subduction zones or tracking the seismicity along oceanic transform faults, mid-ocean ridges, seafloor or island volcanoes and undersea landslides, marine geophysical observations will be key to answering the science questions prioritized by the community in reports like "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" (National Academies of Sciences, Engineering and Medicine, 2020).

This session encourages abstract submissions related to all aspects of marine seismology, particularly in the collection and use of observations through ocean bottom seismographs to record natural and controlled sources. Presentations are also encouraged on related marine geophysical topics such as marine electromagnetic instrumentation and imaging, seafloor geodesy, moored and unmoored hydroacoustic sensors and use of underwater fiber optics, as well as on integration of offshore and onshore technologies and techniques.

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Andrew Gase, University of Texas at Austin (agase@utexas.edu); Joshua Russell, Brown University (joshua_russell@brown.edu); Jianhua Gong, Scripps Institution of Oceanography (j4gong@ucsd.edu); Hannah Mark, Woods Hole Oceanographic Institution (hmark@whoi.edu); Guilherme de Melo, San Diego State University, Scripps Institution of Oceanography (gsampaiodemelo@ucsd.edu); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage

The character and evolution of both natural and induced fracture networks in the deep subsurface remains critical for utilization in both energy (e.g., EGS) and storage (e.g., CO2 or nuclear waste) applications. Additionally, the interactions between induced fractures and the natural structural heterogeneities (i.e., those that govern subsurface flow) remain enigmatic at most meaningful scales. Recent advancements have afforded the research community the opportunity to develop high resolution characterization and monitoring techniques using seismic methods at intermediate to full scale field applications. Additionally, model advancements have allowed for detailed studies of these interactions, although many critical parameters remain poorly constrained. In deep crystalline settings the rock fabric, complex structure, and sometimes severe seismic anisotropy often create challenging characterization environments. In terms of monitoring, energy and storage applications are frequently 4D problems, where the character of the reservoir evolves throughout the active injections (e.g., stress evolution). In these long-term operational scenarios, it is paramount that seismic imaging and characterization approaches be developed and streamlined to provide useful and timely information to operators. Finally, new observations regarding induced seismicity are illuminating complexities beyond stress reduction via increased pore pressures (e.g., thermo-poro-elastic stressing). Improved understanding of these processes bears significantly on seismic hazard assessments. Given the unique challenges to deep subsurface seismic investigations, we invite submissions detailing methods, observations, and modeling studies related to seismic imaging, monitoring and induced seismicity in fractured crystalline rocks and other relevant geologic media applied to energy production or waste storage.

Conveners: D. Parker Sprinkle, University of Washington (dpsprink@uw.edu); Hunter A. Knox, Pacific Northwest National Lab (hunter.knox@pnnl.gov)

Improving Strong-Motion Data, Products and Services: From Waveform Quality to Open Dissemination

Engineering seismology and earthquake engineering require high-quality and easily accessible earthquake waveform data and associated station and event metadata. Providers of event-based waveform data (often referred to as 'strong-motion data' for simplicity) and services worldwide are continuously improving the portfolio of available services in order to meet the expectations of a broad range of users, that includes both scientists and engineering practitioners. Users and funding agencies expect the data, products and services to be open and FAIR (Findable, Accessible, Interoperable, Reusable). While web interfaces remain the preferred way to discover available data, access is increasingly via web services that allow integration in automated processing workflows and enhanced interaction with large datasets. The traditional boundary between weak and strong ground motion records has become blurred, as on-scale weak motion data is proving to be useful in many applications where strong motions would have only been used in the past. In this context, ensuring a high quality of event-based waveform data and metadata is a need and at the same time a challenge. In this session we welcome contributions from the communities of strong-motion/event-based data providers at both a local/national level and an international level to promote knowledge transfer and expert discussion on the strategies to improve earthquake waveform data, metadata and the associated products and services. Topics include: station and waveform quality, station and event metadata curation and integration, new processing algorithms and needs, new data types, formats and open dissemination strategies.

Conveners: Carlo Cauzzi, ORFEUS, SED, ETH Zurich (carlo.cauzzi@sed.ethz.ch); Hamid Haddadi, CGS-CSMIP & COSMOS (hamid.haddadi@conservation.ca.gov); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); Giovanni Lanzano, Istituto Nazionale di Geofisica e Vulcanologia (giovanni.lanzano@ingv.it); Lisa Schleicher, U.S. Geological Survey (lschleicher@usgs.gov); Olga-Joan Ktenidou, GEIN-NOA (olga.ktenidou@noa.gr); Jamison Steidl, University of California, Santa Barbara (steidl@ucsb.edu)

Insights from Earthquakes in and around Alaska in the 20 Years since the Denali Fault Earthquake

This year will mark 20 years since the 3 November 2002 M7.9 Denali Fault Earthquake. The last two decades have seen a number of intriguing and important earthquakes across Alaska, as well as an explosion in the amount of seismic and geodetic instrumentation and data to study them. Notable Alaska earthquakes over the last two decades include the largest earthquake in the United States since 1965 (2021 M8.2 Chignik), the largest intraslab earthquake in the United States (2014 M7.9 Little Sitkin earthquake in the western Aleutians), an earthquake that at least partially filled the enigmatic Shumagin seismic gap (2020 M7.8 Simeonof), the complex Gulf of Alaska earthquake in 2018 and two damaging events in Cook Inlet (2016 Iniskin and 2018 Anchorage). Additional large earthquakes have occurred nearby in the North Pacific region, including the 2012 M7.8 Haida Gwaii earthquake offshore Canada and the 2017 M7.8 earthquake north of the Komandorsky Islands. Meanwhile, observational capabilities have grown dramatically due to the EarthScope program, significant components of which have been incorporated into long-term network capabilities, the continuing enhancement of InSAR measurements and the growth in the number of near-field strong motion recordings.

This session welcomes presentations on all aspects of earthquakes in Alaska and the north Pacific, including western Canada and the Russian Far East. We welcome geological, geodetic and seismological studies, modeling efforts, hazard assessments and integrative studies that address earthquakes in this region and their hazard, seismotectonics and mechanics of fault systems.

Conveners: Jeffrey T. Freymueller, Michigan State University (freymuel@msu.edu); Julie Elliott, Michigan State University (julieelliott.ak@gmail.com); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Lucinda Leonard, University of Victoria (lleonard@uvic.ca); Natalia Ruppert, University of Alaska Fairbanks (naruppert@alaska.edu); Andrew Schaeffer, Geological Survey of Canada (andrew.schaeffer@canada.ca); Derek Schutt, Colorado State University (derek.schutt@colostate.edu); Rob Witter, U.S. Geological Survey (rwitter@usgs.gov)

Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring

Applying Machine-learning (ML) applications to seismic processing problems is increasingly becoming standard for local and near regional networks. However, sparser global and continental scale regional networks present additional challenges that require further development for such methods to be effective. These challenges include the detection and identification of additional phase types (such as local, regional and teleseismic P and S arrivals). Overlap among all arrival types and network sparsity often prevent the direct application of many local and dense network approaches (e.g. those that rely on moveout patterns). Another difference is the broader use of seismic arrays at some networks, such as the International Monitoring System, which provide processing challenges as well as more input features for ML algorithms than are available at most smaller networks. We invite presentations on methods that can enhance the performance of steps commonly taken in both retrospective and near-real-time network processing, such as signal detection, phase identification, event detection/association, event location, event validation, magnitude estimation, event type classification and repeat event tracking, with a focus on methods that reduce analyst workloads, especially during large aftershock sequences. We also invite presentations that combine multiple steps or reimagine processing into novel pipelines enabled by data science methods and/or high performance computing capabilities. The goal of this session is to highlight recent work that improves large scale, sparse network processing and to motivate discussion of new research directions that can address these challenges.

Conveners: G. Eli Baker, Air Force Research Laboratory (g.eli.baker@gmail.com); John Patton, National Earthquake Information Center, U.S. Geological Survey (jpatton@usgs.gov); Josh Dickey, Air Force Technical Applications Center (joshuadickey@gmail.com); Ian McBrearty, Stanford University (imcbrear@stanford.edu); Jesse Williams, Global Technology Inc. (jwilliams@globaltechinc.com)

Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information

Effective and timely post-earthquake response and recovery require a continuous flow of accurate, updated assessments to key decision-makers from a variety of disparate sources. Users know that each source has its own limitations and uncertainties, though there are always challenges in quantifying and communicating them. In the case of the 2021 M7.2 Haiti earthquake, compounding the difficulty in assessing the immediate shaking damage were reports of widespread landslides that added uncertainty as to the cause of remotely assessed physical changes. Further changes resulted from tropical storm rainfall and flooding that began soon after the event. This earthquake emphasized the benefits and importance of modeled hazard and loss estimates, remotely sensed observations and information gathered locally and assessed remotely. Field assessments by numerous international teams were limited due to Haiti's governmental limitations, security concerns and other on-the-ground challenges.

In this session, we solicit studies of all means of contributing to post-event situational awareness for decision-makers, responders and aid agencies, be it from physical or empirical modeling, ground-truth or remotely sensed data collection, or combinations of thereof. We are also intent on gathering experience or evidence of best practices in communicating actionable information and their uncertainties for the 2021 Haiti and other events. Analyses that consider the complexity of response and recovery from simultaneous, cascading and multi-hazard events are particularly welcome.

Conveners: David J. Wald, U.S. Geological Survey (wald@usgs.gov); Heidi Stenner, Geohazards International (stenner@geohaz.org); Eric Fielding, NASA Jet Propulsion Laboratory (eric.j.fielding@jpl.nasa.gov); Haeyoung Noh, Stanford University (noh@stanford.edu); Susu Xu, SUNY Stonybrook (susu.xu@stonybrook.edu); Kate E. Allstadt, U.S. Geological Survey (kallstadt@usgs.gov)

Multi-Scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation

The complexity of earthquake rupture and the parameters that control such behavior is an active area of investigation that includes many challenging research topics. This session will highlight recent advances in rupture dynamics on complex fault systems and their comparison with different types of available observations. We are interested in a wide range of investigations related to numerical, experimental and observational fault rupture studies that examine the effects of fault geometry, fault roughness, frictional parameters, topography, creeping mechanisms, stress asperities, off-fault material properties and plasticity, bi-material interfaces and wedge structures along subduction zones. We also encourage contributions on research that explores links between earthquake source physics, tsunami generation/propagation and ground motion variability.

Conveners: Kenny Ryan, Air Force Research Laboratory (0k.ryan0@gmail.com); Roby Douilly, University of California, Riverside (roby.douilly@ucr.edu); Christodoulos Kyriakopoulos, University of Memphis (ckyrkpls@memphis.edu); Eric L. Geist, U.S. Geological Survey (egeist@usgs.gov); Ruth Harris, U.S. Geological Survey (harris@usgs.gov); David D. Oglesby, University of California, Riverside (david.oglesby@ucr.edu)

Network Seismology: Recent Developments, Challenges and Lessons Learned

Seismic monitoring is not only an essential component of earthquake response but also forms the backbone of a substantial amount of research into seismic hazards, the earthquake process and seismotectonics. As such, it is important to continue to develop monitoring networks' abilities to accurately and rapidly catalog earthquakes to ensure networks best serve the public, government and academic communities. Due to the operational environment of seismic monitoring, seismic networks encounter many unique challenges not seen by the research community. In this session, we highlight the unique observations and challenges of monitoring agencies and look to developments that may improve networks' ability to fulfill their missions. Seismic operation centers play a crucial role in collecting seismic data, generating earthquake products and including catalogs, warnings and maps of ground shaking. The purpose of the session is to foster collaboration between network operators, inform the wider seismological community of the interesting and challenging problems within network seismology and look to the future on how to improve monitoring capabilities. This session is not only an opportunity for monitoring agencies to highlight new developments in their capabilities, but we also encourage submissions describing new techniques that would benefit network operations for detecting, locating and characterizing earthquakes, particularly in a near real-time environment.

Conveners: William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Kris L. Pankow, University of Utah (pankowseis2@gmail.com); Renate Hartog, University of Washington (jrhartog@uw.edu)

New Developments in Physics- and Statistics-Based Earthquake Forecasting

The increasing availability of geophysical datasets, including high-resolution earthquake catalogs, fault information and interseismic strain data, has enabled the creation of statistics- and physics-based seismicity models that underpin probabilistic seismic hazard analyses. Recently, data acquisition has further improved from machine learning (ML) techniques, which paves the way for potentially more informative earthquake forecasts. Earthquake forecasting models express a wide range of hypotheses regarding the occurrence of earthquakes, which can be tested within the framework of the Collaboratory for the Study of Earthquake Predictability (CSEP). We welcome contributions that help uncover the main advantages and limitations of statistical and physics-based seismicity models, identify informative forecasting methods and improve our understanding of the earthquake generation process. Submissions may include forecasting models based on ML-derived catalogs, new hypotheses explaining what controls earthquake potential or evaluations of the predictive skills of earthquake-rate forecasts.

Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); William H. Savran, Southern California Earthquake Center (wsavran@usc.edu); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch)

Numerical Modeling in Seismology: Developments and Applications

We invite both methodological contributions and useful applications. Progress in seismology is unthinkable without continuous development of numerical-modeling methods. Recent methodological development includes faithful rheological and geometrical complexity of the Earth, important seismological phenomena, time-space discretization, optimizations of computational algorithms and computer codes, optional balance between accuracy and efficiency. Recent methodological progress in numerical modeling in seismic exploration poses a useful challenge for numerical modeling in earthquake seismology.

New observations and data make applications of numerical modeling very important for understanding rupture dynamics, seismic wave propagation, earthquake ground motion including non-linear behavior, seismic noise and earthquake hazard. We especially welcome applications to compelling observational issues in seismology.

Conveners: Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Alice-Agnes Gabriel, Ludwig-Maximilians-University of Munich (gabriel@geophysik.uni-muenchen.de); Wei Zhang, Southern University of Science and Technology Shenzhen (zhangwei@sustech.edu.cn); Emmanuel Chaljub, Université Grenoble Alpes (emmanuel.chaljub@univ-grenoble-alpes.fr); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov)

Observations and Modeling of the 2021 Haiti Earthquake

The August 14, 2021 Mw7.2 Nippes, Haiti earthquake ruptured along the Enriquillo-Plantain Garden Fault Zone (EPGFZ), about 100 km west of the devastating 2010 Mw7.0 Leogane, Haiti earthquake. The EPGFZ is part of a system of strike slip and thrust faults that comprise the transpressive boundary between the North American and Caribbean plate. In this session, we plan to highlight observations and models of this rupture sequence, informing the ongoing debate on how this complex fault system partitions strain as it transitions from subduction to strike-slip regimes. In bringing together the latest observations and models of the 2021 earthquake, we hope to forge new perspectives on ongoing seismic hazards in the region.

We welcome all abstract submissions related to observations and models of the 2021 earthquake. This includes rupture imaging, relocated aftershock sequences, field observations, surface rupture observations, ground failure observations, landslide observations, rupture modeling and hazard modeling. Submissions with retrospective analyses of the 2010 earthquake that shed light on the broader context of the earthquake sequence are also welcome.

Conveners: H. Zoe Yin, University of California, San Diego (hyin@ucsd.edu); Alice-Agnes Gabriel, Ludwig Maximilian University of Munich (alice.gabriel@web.de); Roby Douilly, University of California, Riverside (robyd@ucr.edu)

Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?

Probabilistic seismic hazard assessments (PSHA) are widely used in building codes and other standards and guidelines in determination of seismic loads for seismic resistant design. Many types of input go into PSHA, such as an earthquake catalogues (requiring a robust assessment of earthquake magnitudes, locations, depths, etc.), active fault information (geometry, sense of motion on the fault, recurrence and slip rate estimates, etc.) and prediction of strong ground motion through ground motion models (GMMs), which can be empirical. GMMs require large amounts of recorded strong motion or analytical data and simulations that may have varying degrees of sophistication. In addition, PSHA is increasingly conducted for multiple ground conditions rather than being pegged to a "reference" site condition characterized in terms of Vs30. In this session we discuss how to rethink and improve some of these inputs, keeping in mind the end goal of determining seismic loads for engineering design. To that end, we welcome contributions related to topics including but not limited to: improvements in moment magnitude calculations and magnitude conversions; earthquake relocations; how to improve upon declustering earthquake catalogues for PSHA purposes; how to incorporate our current knowledge in active faults into PSHA, particularly in places where that knowledge is sparse; whether we can move beyond "active" and "stable" crustal GMMs to adequately capture the variation in attenuation characteristics for shallow crustal earthquakes; objective vs. subjective decision making in selecting GMMs and how simulations can help resolve some important issues around ground motion characterization in PSHA.

Conveners: Tuna Onur, Onur Seemann Consulting, Inc. (tuna@onurseemann.com); Rengin Gok, Lawrence Livermore National Laboratory (gok1@llnl.gov); Kristin Morell, University of California, Santa Barbara (kmorell@geol.ucsb.edu); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov); Mark Petersen, U.S. Geological Survey (mpetersen@usgs.gov)

Searching for Fault Creep Over a Range of Timescales

Creep is well-expressed on fast slipping faults in developed areas (ex: the Hayward fault, California). In the absence of fault creep, geoscientists often assume that all fault slip over historic and geologic time scale is accommodated seismically. However, this assumption is not currently testable as the broader earthquake hazard community does not have well-developed methods for distinguishing seismic from aseismic transient displacement in the geologic record. The impacts of this assumption on hazard assessment are likely profound. How much does interseismic creep contribute to periodic, quasi-periodic, random or clustered earthquake recurrence? What is the impact on the spatio-temporal distribution of microseismicity, geologic slip rate calculations and earthquake rupture forecasting?

This session seeks to understand geologic, geodetic, seismologic, numerical and physical modeling insights into including the following: 1) What are observations of creep in the geodetic, paleoseismic and geologic record?; 2) When does shallow aseismic occur during the seismic cycle?; 3) Does lithology impact the distribution and preservation of creep?; 4) Do fault zone mechanical and physical properties control creeping versus seismic behavior?; 5) What do creeping faults teach us about seismogenic faults? and 6) What is missed in hazard by misidentifying aseismic as coseismic slip? We invite contributions that aim to answer these or other questions for creeping faults.

Conveners: Alexandra E. Hatem, U.S. Geological Survey (ahatem@usgs.gov); Veronica Prush, McGill University (vbprush@ucdavis.edu); Christie Rowe, McGill University (christie.rowe@mcgill.ca); Chelsea Scott, Arizona State University (cpscott1@asu.edu)

Seismo-Geodetic Approaches for Seismic and Tectonic Processes

Geodetic tools have become routine in studies of tectonic plate motions, ground deformation, dynamic seismic observations, earthquake early warning and short-/long-term seismic hazard projections. Geodesy complements seismic observations by increasing the spatial resolution of seismic source models, spatially and temporally characterizing tectonic deformation and providing additional constraints on seismic processes. Advances to geodetic data processing and its incorporation in evolving seismological methods contribute to faster and more reliable seismic and disaster-mitigation applications.

This session welcomes contributions in the field of seismo-geodesy. We invite abstracts relating to any geodetic tool (e.g., GNSS, InSAR, strain, etc.) demonstrating new applications, improvements or analyses of tectonic deformation, specific earthquakes or sequences or other seismic processes with geodetic observations. We encourage submissions that illustrate the complementary nature of geodetic methods to their seismological counterparts, providing a comprehensive picture of a given seismic or tectonic process.

Conveners: Revathy M. Parameswaran, University of Alaska Fairbanks (rmparameswaran@alaska.edu); Dara E. Goldberg, U.S. Geological Survey (degoldberg@usgs.gov)

Shakes in Lakes: Frontiers in Lacustrine Paleoseismology

Lacustrine paleoseismology studies show that lakes can provide superior records of earthquake shaking for hazard analysis and understanding earthquake behavior. Earthquake-induced strong ground motions can result in the mobilization and redeposition of sediments in lakes. Thus, records of earthquake shaking can extend thousands of years with near annual resolution and be sensitive to earthquakes with Modified Mercalli Intensities as low as IV½. These advantages can provide a much more complete record of earthquake shaking than traditional paleoseismic records from trenches or coastal marshes, although single-lake records are generally agnostic of the seismic source. Uniquely, lakes can record earthquake shaking from seismic sources that cannot be directly examined, such as intraslab or intraplate events. And multi-lake records in some regions show high potential for resolving source faults.

We invite presentations on all aspects of the emerging field of lacustrine paleoseismology and potential uses of these records. We encourage presentations on the following topics: tectonic settings and types of lake environments, the discrimination between earthquake and climatically induced turbidites, the links between deposit characteristics and shaking parameters (MMI, duration, PGA), the evaluation of seismic sources and the novel ways of including these data in hazard evaluation.

Conveners: Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Maarten Van Daele, Ghent University (maarten.vandaele@ugent.be); Jamie Howarth, Victoria University of Wellington (jamie.howarth@vuw.ac.nz)

Site Response Characterization in Seismic Hazard Analysis

Ergodic ground motion models (GMMs) represent site response (SR) as a function of explanatory variables, such as V S30 (time-averaged shear wave velocity in the top 30 m). Such SR models make the ergodic assumption that any sites with the same values of explanatory variables will have the same SR. However, it is well known that the SR at a given site (non-ergodic site response, NESR) can significantly differ from that estimated by the ergodic SR model. Moreover, when applied to scenarios for which the empirical observations are sparse (e.g. V S30 > 1500 m/s), ergodic SR estimates from the GMMs could be systematically biased. To perform site response characterization (SRC) for a site of interest, 1D ground response analyses (GRA) are often performed, requiring SR input parameters such as a V S profile to derive a model-based NESR (M-NESR). An alternative approach uses ground motion recordings at the site of interest to perform SRC and derive an empirical NESR (E-NESR), without the need to perform GRA or make assumptions on GRA model and input parameters.

This session solicits a broad range of approaches used for SRC. Topics of interest include active-/passive geophysical surveys (e.g., linear/2D, single-/multi-station surface-based array methods, down-/cross-hole methods, seismic interferometry, etc.) to develop M-NESR, studies using site-specific recordings to derive E-NESR, the use of machine learning in SRC and studies comparing results from different techniques and their associated epistemic uncertainties. Of special interest are studies performing SRC outside the applicable range of ergodic GMMs (e.g. V S30 > 1500 m/s); studies on improving current practice in SRC, e.g., the search of optimal SR proxy (beyond V S30 or site dominant frequency); 2D/3D site effects; SR uncertainty and variability; soil nonlinearity; the effect of topography and fractured rocks on ground motion amplification and attenuation and integration of site effects into seismic hazard analysis.

Conveners: Behzad Hassani, BC Hydro (behzad.hassani@bchydro.com); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Sean K. Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Gail M. Atkinson, Western University (gmatkinson@aol.com); Anna Kaiser, GNS Science (a.kaiser@gns.cri.nz); Marta Pischiutta, Istituto Nazionale di Geofisica e Vulcanologia (marta.pischiutta@ingv.it); Jonathan P. Stewart, University of California Los Angeles (jstewart@seas.ucla.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin@gfz-potsdam.de)

Structure and Seismogenesis of Subducting Slabs

Sinking slabs provide the major force that drives Earth's interior dynamics and plate tectonics. They also carry volatiles such as water and CO_2 into the deep mantle and impact the geochemical evolution of the Earth. Deep earthquakes (depth > 70 km) are absent in the mantle except in subducting slabs, mantle wedges, or regions of continental convergence. They can be further categorized as intermediate-depth earthquakes (70-350 km depth) and deep-focus earthquakes (350-700 km). Their causes and mechanisms remain a major scientific puzzle.

In this session, we invite contributions that characterize the structure and properties of subducting slabs, as well as new findings about deep earthquakes. We welcome observational, theoretical and numerical modeling results, as well as those from laboratory and field studies. New ideas and/or unusual observations, supported by numerical modeling, on how to study slabs and deep earthquakes are also welcome. Relevant techniques may include, but are not limited to seismic imaging, waveform inversion, seismic anisotropy, moment tensors, precise location of deep earthquakes and their statistical behaviors. Broader scientific issues to be addressed may include constraints on deep seismogenesis, slab structure and stress in subducting slabs, as well as interactions between these topics.

Conveners: Yingcai Zheng, University of Houston (yzheng12@uh.edu); Neala Creasy, Colorado School of Mines (nmcreasy@mines.edu); Heidi Houston, University of Southern California (houstonh@usc.edu); Zhigang Peng, Georgia Tech (zpeng@gatech.edu); German A. Prieto, Universidad Nacional de Colombia (gaprietogo@unal.edu.co)

Tectonics and Seismicity of Intraplate Regions

Far from active plate boundaries, in stable continental interiors of central and eastern North America, northern Europe, Australia, parts of Asia, as well as in some offshore regions, tectonic deformation and seismicity are poorly known. New understandings of intraplate tectonic activity and associated seismicity are being achieved through a variety of approaches. Some take advantage of recent local, regional or national-scale geophysical experiments, using various technologies to monitor or image both onshore and offshore regions. Detailed studies of individual recent earthquakes or sequences and new methods of identifying smaller earthquakes from existing data have provided insights into subsurface faulting. Moreover, advances are being made in measuring historical slip on faults and estimating recurrence intervals. Our understanding has also increased from investigations of geodetic, geomorphologic and elevation changes and through improved measurements of local stresses. Complementing these approaches are studies that focus on ground motion attenuation and local site responses in continental interior regions, highlighting the impact intraplate earthquakes can have on seismic hazard assessments.

This session seeks diverse contributions related to intraplate earthquakes with goals of describing seismicity, identifying and characterizing active faults and/or deformation in stable continental interiors or offshore regions, deciphering long-term earthquake histories, assessing potential ground motion impacts, constraining models of kinematics and geodynamic properties and understanding the mechanisms that cause enigmatic intraplate earthquakes.

Conveners: Anjana K. Shah, U.S. Geological Survey (ashah@usgs.gov); Francesca Di Luccio, Istituto Nazionale di Geofisica e Vulcanologia, ROMA1 (francesca.diluccio@ingv.it); Will Levandowski, TetraTech (bouldergeophysics@gmail.com); Mimmo Palano, Istituto Nazionale di Geofisica e Vulcanologia, OE (mimmo.palano@ingv.it); Laura Scognamiglio, Istituto Nazionale di Geofisica e Vulcanologia, ONT (laura.scognamiglio@ingv.it)

Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources

Although earthquakes are well known sources of seismic and acoustic energy, there are many others that produce such signals, which can occasionally perplex scientists: explosions, underground cavity collapses, landslides, volcanic activity and human activities (planned and accidental), to name just a few. This session focuses on improvements in methods to detect these types of sources and identify what causes them amid the background of the Earth's seismicity. We seek studies that can better characterize these sources in terms of their location, size and physics with a goal of better explaining what happened to produce such signals. Many techniques have been used over the years to accomplish this task including: seismic/acoustic energy partitioning; moment tensor characterization through waveform modeling; P/S, low/high frequency, Rayleigh/Love and other types of seismic amplitude ratios; as well as many types of magnitude ratios such as m_b:M_s and M_L:M_c. The successful methods vary greatly with source to receiver distance and frequency content in ways that are not completely understood. More recently waveform correlation methods have had great success in identifying repeated sources and can be used to drive down detection levels for such events. Most recently, when appropriate training data are available, machine learning and methods are being explored for these purposes. In this session we seek studies on all types of non-earthquake seismic acoustic sources and the methods used to find and describe them.

Conveners: William R. Walter, Lawrence Livermore National Laboratory (walter5@llnl.gov); Catherine M. Snelson, Los Alamos National Laboratory (snelsonc@lanl.gov); Robert E. Abbott, Sandia National Laboratories (reabbot@sandia.gov)

Using Data and Experience to Improve Geohazards Communication

Effective communication of potential and unfolding geohazards and the science that underpins our understanding of these hazards is critical for delivering accurate information to various stakeholders, including religious, community and government leaders, scientists, emergency responders and managers, and the interested and at-risk public. While good communication techniques are paramount in any science communication, geohazards communication requires special considerations and different groups, organizations and universities may play different (but key) roles in the communication process.

This session aims to 1) explore research-based evidence and case studies of communicating about geohazards through various types of media and to different communities, 2) share lessons learned and best practices for communicating geohazards in the public sphere and 3) facilitate community-wide discussion about how we can more accurately, effectively and responsibly communicate geohazards science to a broad audience using various media and communications partnerships.

Conveners: Wendy Bohon, Incorporated Research Institutions for Seismology (wendy.bohon@iris.edu); Scott Johnson, UNAVCO (scott.johnson@unavco.org); Lisa Wald, U.S. Geological Survey (lisa@usgs.gov)

What Controls the Style of Fault Slip in Subduction Zones?

The heterogeneous structure of the plate boundary fault zone has a first-order impact on the style of fault slip that occurs at the subduction interface, both within the megathrust and neighboring regions of the seismogenic zone where slow earthquakes occur. For example, subducting seamounts appear to control the segmentation of the megathrust; at a smaller scale, tremor-generating seismic asperities are spatially stationary across multiple slow slip events that each have their own unique rupture evolution. Other controls on structure such as lithology, elevated pore fluid pressures and changing stress states can also play a role in determining faulting style. The outstanding question we would like to address is: what is the impact of subducting plate interface structure on the broad spectrum of faulting that is observed?

We seek abstracts that shed light on the impact of such fault structure (including but not limited to heterogeneity, lithology, pore fluid pressure and stress state) on the mode of fault slip. We welcome abstracts focused on individual aspects of structure and faulting dynamics, including but not limited to geophysical imaging, earthquake source, and numerical modeling studies, whose connections will be explored within the greater context of the session. Our hope is that this session will build off of, and contribute to, the momentum surrounding the community-driven Subduction Zones in 4 Dimensions (SZ4D) initiative.

Conveners: Qingyu Wang, Massachusetts Institute of Technology (qingyuwa@mit.edu); Alice-Agnes Gabriel, Ludwig Maximilian University of Munich (alice.gabriel@web.de); Keisuke Yoshida, Tohoku University (keisuke.yoshida.d7@tohoku.ac.jp); William B. Frank, Massachusetts Institute of Technology (wfrank@mit.edu)

Overview of Technical Program

Tuesday 19 April

9 AM–Noon
Workshop: Introduction to Machine Learning

1–4 PM
Workshop: Machine Learning II

1–4 PM
Workshop: Publishing–How to Review and How to Be Reviewed

3–7 PM
Registration Open

4–5:30 PM
Opening Reception

5:30–6:30 PM
Keynote Plenary: The Cascadia Margin Revealed

6:30–8 PM
Newcomers Welcome Event

Wednesday 20 April

8–9:15 AM
Oral Sessions

9:15–10 AM
Poster Break

10–11:15 AM
Oral Sessions

11:30 AM–12:30 PM
Plenary: Science and Technology from a Makah Perspective

12:30–2 PM
Lunch Break

2–3:15 PM
Oral Sessions

3:15–4:30 PM
Poster Break

4:30–5:45 PM
Oral Sessions

6–7 PM
Plenary: The Future of Subduction Zone Science

7–8 PM
Early-Career & Student Reception

Thursday 21 April

8–9:15 AM
Oral Sessions

9:15–10 AM
Poster Break

10–11:15 AM
Oral Sessions

11:30 AM–12:30 PM
SSA President's Address and Awards Ceremony

12:30–2 PM
Lunch Break

2–3:15 PM
Oral Sessions

3:15–4:30 PM
Poster Break

4:30–5:45 PM
Oral Sessions

6–7 PM
Plenary: Joyner Lecture

7–8 PM
Joyner Reception

Friday 22 April

8–9:15 AM
Oral Sessions

9:15–10 AM
Poster Break

10–11:15 AM
Oral Sessions

11:30 AM–12:30 PM
Plenary: Frontiers in Seismology

12:30–2 PM
Lunch Break

2–3:15 PM
Oral Sessions

3:15–4:30 PM
Poster Break

4:30–5:45 PM
Oral Sessions

Saturday 23 April

7–10:15 AM
Field Trip: First Light Kayak Tour on Lake Washington

7 AM–10 PM
Field Trip: Cascadia by Canoe

7:30 AM–6:30 PM
Field Trip: Seattle Geology

Wednesday, 20 April

Oral Sessions

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K*	*Cedar*	*Regency A–C*	*Regency E–G*
8:00–9:15 AM	Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources	De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances	Advancing Multi-scale Evaluations of Seismic Attenuation	50-State Update of the USGS National Seismic Hazard Models	Tectonics and Seismicity of Intraplate Regions	Numerical Modeling in Seismology: Developments and Applications	Advances in Geophysical Sensing
9:15–10:00 AM	Poster Break						
10:00–11:15 AM	Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources (*continued*)	De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances (*continued*)	Advancing Multi-scale Evaluations of Seismic Attenuation (*continued*)		Tectonics and Seismicity of Intraplate Regions (*continued*)	Numerical Modeling in Seismology: Developments and Applications (*continued*)	50-State Update of the USGS National Seismic Hazard Models
11:30 AM–12:30 PM	*Plenary*: Science and Technology from a Makah Perspective—Incorporation of Native American Knowledge Systems						
12:30–2:00 PM	Lunch Break						
2:00–3:15 PM	Fault Damage Zones: What We Know and Do Not	Using Data and Experience to Improve Geohazards Communication	Advances in Geospatial Modeling of Seismic Hazards	What Controls the Style of Fault Slip in Subduction Zones?	The Effects of Sedimentary Basins on Earthquake Ground Motions	Tectonics and Seismicity of Intraplate Regions	50-State Update of the USGS National Seismic Hazard Models
3:15–4:30 PM	Poster Break						
4:30–5:45 PM	Fault Damage Zones: What We Know and Do Not (*continued*)	Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination	Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage		The Effects of Sedimentary Basins on Earthquake Ground Motions (*continued*)	Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information	What Controls the Style of Fault Slip in Subduction Zones?
6:00–7:00 PM	*Plenary*: The Future of Subduction Zone Science						
7:00–8:00 PM	Early-Career & Student Reception						

Poster Sessions

- 50-State Update of the USGS National Seismic Hazard Models
- Adjoint Waveform Tomography: Methods and Applications
- Advances in Geophysical Sensing
- Advances in Geospatial Modeling of Seismic Hazards
- Advancing Multi-scale Evaluations of Seismic Attenuation
- De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances
- Diversity, Equity and Inclusion in Seismology
- The Effects of Sedimentary Basins on Earthquake Ground Motions
- Exploring Earthquake Source Dynamics and Wave Propagation Properties in Tectonic and Lab Environments
- From Desktops to HPC & Cloud: Emerging Strategies in Large-scale Geophysical Data Analysis
- Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage
- Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination
- Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information
- Numerical Modeling in Seismology: Developments and Applications
- Observations and Modeling of the 2021 Haiti Earthquake
- Searching for Fault Creep Over a Range of Timescales
- Tectonics and Seismicity of Intraplate Regions
- Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources
- Using Data and Experience to Improve Geohazards Communication
- What Controls the Style of Fault Slip in Subduction Zones?

Thursday, 21 April

Oral Sessions

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K*	*Cedar*	*Regency A–C*	*Regency E–G*
8:00–9:15 AM	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?	Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone	The 15 January 2022 Tonga Eruption and Tsunami	Earthquake Source Processes at Various Scales: Theory and Observations	Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science	The Effects of Sedimentary Basins on Earthquake Ground Motions	Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring
9:15–10:00 AM	Poster Break						
10:00–11:15 AM	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (*continued*)	Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone (*continued*)	Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors		Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science (*continued*)	Earthquake Source Processes at Various Scales: Theory and Observations (*continued*)	Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring (*continued*)
11:30 AM–12:30 PM	SSA President's Address and Awards Ceremony						
12:30–2:00 PM	Lunch Break						
2:00–3:15 PM	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?		Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science (*continued*)	The 15 January 2022 Tonga Eruption and Tsunami	Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors	Shakes in Lakes: Frontiers in Lacustrine Paleoseismology	Seismogeodetic Approaches for Seismic and Tectonic Processes
3:15–4:30 PM	Poster Break						
4:30–5:45 PM	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (*continued*)		Development, Enhancement and Validation of Seismic Velocity Models		The 15 January 2022 Tonga Eruption and Tsunami (*continued*)	Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere	Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake
6:00 PM–7:00 PM	*Plenary:* Joyner Lecture						

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K*	*Cedar*	*Regency A–C*	*Regency E–G*
7:00 PM–8:00 PM	Joyner Reception						

Poster Sessions

- The 15 January 2022 Tonga Eruption and Tsunami
- Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science
- Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone
- Development, Enhancement and Validation of Seismic Velocity Models
- Earthquake Source Processes at Various Scales: Theory and Observations
- Everything Old Is New Again—Resurging Use of Analog Data
- Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere
- Fault Damage Zones: What We Know and Do Not
- Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors
- Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake
- Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring
- Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?
- Seismo-geodetic Approaches for Seismic and Tectonic Processes
- Shakes in Lakes: Frontiers in Lacustrine Paleoseismology

Friday, 22 April

Oral Sessions

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K*	*Cedar*	*Regency A–C*	*Regency E–G*
8:00–9:15 AM	Earthquakes in the Urban Environment	New Developments in Physics- and Statistics-based Earthquake Forecasting	Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions	Earthquake Source Processes at Various Scales: Theory and Observations	Advances in Seismoacoustic Methods for Explosion Monitoring	Distributed Deformation from Surface Fault Rupture	Site Response Characterization in Seismic Hazard Analysis
9:15–10:00 AM	Poster Break						
10:00–11:15 AM	Earthquakes in the Urban Environment (*continued*)	New Developments in Physics- and Statistics-based Earthquake Forecasting (*continued*)	Structure and Seismogenesis of Subducting Slabs		Advances in Seismoacoustic Methods for Explosion Monitoring (*continued*)	Earthquake Source Processes at Various Scales: Theory and Observations	Site Response Characterization in Seismic Hazard Analysis (*continued*)
11:30 AM–12:30 PM	Plenary: Frontiers in Seismology						
12:30–2:00 PM	Lunch Break						
2:00–3:15 PM	Network Seismology: Recent Developments, Challenges and Lessons Learned	Adjoint Waveform Tomography: Methods and Applications	Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation	Structure and Seismogenesis of Subducting Slabs	Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy	Advances in Seismoacoustic Methods for Explosion Monitoring (*continued*)	Site Response Characterization in Seismic Hazard Analysis (*continued*)
3:15–4:30 PM	Poster Break						
4:30–5:45 PM		Adjoint Waveform Tomography: Methods and Applications (*continued*)		Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes	Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy (*continued*)	Network Seismology: Recent Developments, Challenges and Lessons Learned (*continued*)	Frontiers in Marine Seismology

Poster Sessions

- Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy
- Advances in Seismoacoustic Methods for Explosion Monitoring
- Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes
- Distributed Deformation from Surface Fault Rupture
- Earthquakes in the Urban Environment
- Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions
- Frontiers in Marine Seismology
- Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation
- New Developments in Physics- and Statistics-based Earthquake Forecasting
- Network Seismology: Recent Developments, Challenges and Lessons Learned
- Structure and Seismogenesis of Subducting Slabs
- Site Response Characterization in Seismic Hazard Analysis

Wednesday, 20 April 2022—Oral Sessions

Presenting author is indicated in bold.

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources (see page 1354).	**De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances** (see page 1242).	**Advancing Multi-scale Evaluations of Seismic Attenuation** (see page 1234).	**50-State Update of the USGS National Seismic Hazard Models** (see page 1193).
8:00 AM	STUDENT: Oceanic Microseisms in Alaska. **John, S.**, West, M. E.	Managing Induced Seismicity in Near-real Time: A Case History from Finland. Malin, P. E. A., **Passmore, K.**, Kwiatek, G., Dresen, G., Chendorain, M., *et al.*	INVITED: Some Remarks on Seismic Attenuation in Shallow Geological Layers. **Parolai, S.**	INVITED: 2023 US 50-State National Seismic Hazard Model. **Petersen, M. D.**, Shumway, A. M., Powers, P. M., Field, E. H., Moschetti, M. P., *et al.*
8:15 AM	STUDENT: Analysis of Sustained and Extensive Tidally Triggered Seismicity on the Ross Ice Shelf. **Eckert, E. E.**	Rupture Behaviour of Geothermal Fluid-induced Microseismicity from Combining Directivity and Focal Mechanisms in Helsinki, Finland. **Holmgren, J. M.**, Kwiatek, G., Werner, M. J.	INVITED: The Good, the Bad and the Ugly: Investigating Bias in High-frequency Attenuation Using Noise Modeling. **Ktenidou, O.**, Pikoulis, E.	The 2023 Update of the Alaska National Seismic Hazard Model. **Powers, P. M.**, Altekruse, J. M., Clayton, B. S., Shumway, A. M., Girot, D. L.
8:30 AM	Insights From Trapped Seismic Waves in Antarctic Firn Columns: Flow Related Anisotropy, Temporal Monitoring and Rayleigh Wave Behaviors. **Chaput, J.**, Aster, R., Karplus, M., Nakata, N., Gerstoft, P., *et al.*	Seismic Analysis of Reservoir Conditions for Inducing Seismicity at the San Emidio Geothermal Field, Nevada, USA. **Guo, H.**, Thurber, C., Heath, B., Cardiff, M., Lord, N., *et al.*	Time-dependencies of κ. **Haendel, A.**, Cotton, F., Pilz, M.	Sensitivity Testing the 2023 Update of the National Seismic Hazard Model. **Altekruse, J. M.**, Powers, P. M., Clayton, B. S., Shumway, A. M., Girot, D. L.
8:45 AM	Identifying Stable Body-wave Sources for Correlation-based Seismic Velocity Monitoring. **Sheng, Y.**, Mordret, A., Brenguier, F., Boué, P., Vernon, F., *et al.*	Reducing Risk in Geothermal Projects Through Improved Understanding and Characterization of Stimulated Fracture Heterogeneity. **Doe, T.**, Kneafsey, T., Huang, L., Rodríguez Tribaldos, V., Johnson, T., *et al.*	STUDENT: The Variation of Kappa With Induced Shear Strain and the Accuracy of High Frequency Components of Site Response Analyses. **Normand, M.**, Rathje, E. M.	Earthquake Scenario Development in the 2023 USGS National Seismic Hazard Model Update. **Chase, R. E.**, Jaiswal, K. S., Petersen, M. D.
9:00 AM	Characterizing Emergent and Impulsive Non-tectonic Signals in Seismic Waveforms. **Johnson, C.**	INVITED: STUDENT: Statistical Bounds on How Induced Seismicity Stops. **Schultz, R.**, Ellsworth, W. L., Beroza, G. C.	What Does Kappa Mean in Nonlinear Site Response Analyses? **Ji, C.**, Cabas, A., Bonilla, L., Gelis, C., Gann, C.	An Argument for Time-dependent National Seismic Hazard Maps. **Wong, I. G.**, Thomas, P.

Time	Cedar*	Regency A–C	Regency E–G
	Tectonics and Seismicity of Intraplate Regions (see page 1349).	**Numerical Modeling in Seismology: Developments and Applications** (see page 1321).	**Advances in Geophysical Sensing** (see page 1216).
8:00 AM	INVITED: Where Does the Intraplate Tectonic Activity Originate From? Examples From the Adriatic Plate. **Stipčević, J.,** Herak, M., Sečanj, M., Tomljenović, B., Dasović, I., Latečki, H.	A Discontinuous Galerkin Method for Sequences of Earthquakes and Aseismic Slip on Multiple Faults Using Unstructured Curvilinear Grids. **Gabriel, A.**, Uphoff, C., May, D.	Multiplexing Optical Sensors for Expanded Geodetic and Seismic Coverage of the Seafloor. **Zumberge, M.**
8:15 AM	STUDENT: From the 2009 L'aquila Earthquake to the 2016 Amatrice-Visso-Norcia Sequence: 8 Years of Seismicity in Central Italy. **Cabrera, L.**, Poli, P.	The Finite-difference Modeling of Seismic Waves in Media With Poroelastic/Elastic Interfaces. Gregor, D., **Moczo, P.**, Kristek, J., Mesgouez, A., Lefeuve-Mesgouez, G., *et al.*	INVITED: STUDENT: Understanding and Exploiting Ocean Wave Signals in DAS Data. **Williams, E. F.**, Zhan, Z.
8:30 AM	STUDENT: What Is Driving the Different Types of Seismicity Related to the Alto-Tiberina Fault in Italy? Insights From a High-resolution Seismic Catalog. **Essing, D.**, Poli, P.	STUDENT: 3D Simulation of Seismic Response of the Long Valley Embankment Dam, California. **Yeh, T.**, Olsen, K. B.	Digital Quartz Crystal Seismic and Oceanic Sensors. **Venkateswara, K.**, Paros, J., Bodin, P., Tobin, H., Wilcock, W. S. D.
8:45 AM	Intraplate Earthquakes Near Lisbon, Portugal and the 1755 Conundrum. **Fonseca, J. F. D.**	An Improvement of Corner-frequency Modeling for Stochastic Finite-fault Ground Motion Simulation. **Tang, Y.**	STUDENT: Demonstrating a Kalman Filter Fusion of Acceleration, GNSS and Rotational Sensors Using a Flexible Foot Bridge. **Rossi, Y.**, Hohensinn, R., Tatsis, K., Clinton, J. F., Chatzi, E., *et al.*
9:00 AM	A Conceptual Seismological Model for the Norwegian Rifted Margin Drawn from the Perspective Hyperextension. **Redfield, T. F.**, Osmundsen, P. T.	How Does Spatial Variability of Soil Properties Affect Seismic Response of Slopes? **Mohammadi, K.**, Medina, R. J. R., Sánchez-Sesma, F. J.	Observations of Natural and Induced Seismic Events Using Slim Borehole Adapted SiA Sensors. Blumle, F., Avenson, B., Passmore, K., Hofstetter, A., Boese, C., Malin, P. E. A., **Zimakov, L. G.**

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
9:15–10:00 AM	Poster Break			
	Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources (see page 1354).	**De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances** (see page 1242).	**Advancing Multi-scale Evaluations of Seismic Attenuation** (see page 1234).	
10:00 AM	A Semi-empirical Method for Producing Broadband Synthetic Seismograms for Large, Rapid Landslide Scenarios. **Allstadt, K. E.**, George, D.	Local Seismic Monitoring of a Stimulation at the Utah Frontier Observatory for Research in Geothermal Energy Site. **Pankow, K. L.**, Rutledge, J., Dyer, B., Burlacu, R., Bradshaw, P., *et al.*	Observation and Model of Scattering Attenuation of 500 +- 200 Hz Induced Seismic Emissions. **Malin, P. E. A.**, Leary, P. C.	
10:15 AM	Seismo-acoustic Characteristics of the Cooling Tower of a Research Nuclear Reactor. **Chai, C.**, Maceira, M., Marcillo, O.	Seismic Monitoring Around a Potential Deep Geothermal Site in Upstate New York: CorNET. **Abers, G. A.**, Katz, Z. S., Pritchard, M. E., Fulton, P., Gustafson, O., *et al.*	Geometric Spreading and Apparent Anelastic Attenuation of Response Spectral Accelerations. **Graizer, V.**	
10:30 AM	STUDENT: Kinematic Source Inversion of Acoustic-seismic Signals of a Meteoroid Explosion Recorded on a Large-N Seismic Network and Fibre Optic Cables. **Isken, M. P.**, Dahm, T., Rodriguez, I. V., Lamb, O. D., Heimann, S., *et al.*	The DEEP Project: Establishing a Full-scale Real-time Test Bench for Seismic Monitoring and Forecasting at the Utah FORGE EGS Site. **Lanza, F.**, Wiemer, S., The DEEP Team,	STUDENT: Uppermost Mantle Pn-wave Attenuation in the Anatolian Plateau and Surrounding Regions. **Zhu, W.**, Zhao, L., Xie, X., Yao, Z.	
10:45 AM	On the Seismic Equivalence of Chemical and Nuclear Explosions: Insights for the Source Physics Experiment. Vitali, E., **Ford, S. R.**	STUDENT: Induced Micro-seismicity Monitoring in Urban Context Using Seismic Arrays. **Fiori, R.**, Vergne, J., Schmittbuhl, J., Dimitri, Z., Lambotte, S.	STUDENT: Tasman Line in Eastern Australia Constrained by Regional Lg-wave Q Tomography. **You, B.**, Zhao, L., Li, H., Xie, X., Yang, G., *et al.*	

Time	*Cedar**	*Regency A–C*	*Regency E–G*
9:15–10:00 AM	Poster Break		
	Tectonics and Seismicity of Intraplate Regions (see page 1349).	**Numerical Modeling in Seismology: Developments and Applications** (see page 1321).	**50-State Update of the USGS National Seismic Hazard Models** (see page 1193).
10:00 AM	INVITED: Detecting Surficial Evidence of Low-rate Deformation in the Central and Eastern United States. **Jobe, J. A. T.**, Briggs, R. W., Gold, R.	STUDENT: Qualitative and Quantitative Validation of Local Site Response and Spatial Attenuation From Numerically Simulated Ground Motions. **Saxena, S.**, Motamed, R., Ryan, K. L.	INVITED: Overview of Earthquake Rupture Forecasts for the 2023 USGS NSHM Update. **Field, E. H.**
10:15 AM	Complex Fault Segmentation in the New Madrid Seismic Zone Inferred From Seismicity Clustering. **Langston, C. A.**, Powell, C. A.	STUDENT: Can Higher-order Finite-difference Operators Be Applied Across a Material Interface? Moczo, P., **Valovcan, J.**, Kristek, J., Gregor, D.	Lower Seismogenic Depth Model of the Western US Based on Seismicity. **Zeng, Y.**, Petersen, M. D.
10:30 AM	Using Swarms of Small Earthquakes to Look for Seismically Active Structures in Northeastern North America. **Ebel, J. E.**	Numerical Modeling of Earthquake Ground Motion in Georgia Basin Resulting Amplification and Elongation of Events Duration, Greater Vancouver Area, British Columbia. **Oveisy, A.**, Ventura, C.	Early Results From Deformation Models of the Western US for the 2023 Update to the US National Seismic Hazard Model. **Pollitz, F. F.**, Evans, E. L., Field, E. H., Hatem, A. E., Hearn, E. H., *et al.*
10:45 AM	Preliminary Analysis of Seismic Data Recorded by a Temporary Deployment Around the Source Zone of the 1886 M 7 South Carolina Earthquake. **Peng, Z.**, Jaume, S., Daniels, C., Zhai, Q.	Simulation of Underground Chemical Explosions in Soft Alluvium, Hard Granite, Brittle Tuff and Salt Formations Using Anisotropic Hydrodynamic Generated Source Coupled to Linear Anisotropic Wave Propagation. **Ezzedine, S. M.**, Vorobiev, O., Pitarka, A., Antoun, T., Walter, W. R.	Proposed Updates to the UCERF3 Fault System Inversion Approach for Use in the 2023 Western US ERF. **Milner, K. R.**, Field, E. H.

Time	Grand A	Grand B	Grand C	Grand E–K*
	Things That Go Bump…	**De-risking Deep Geothermal Projects…**	**Advancing Multi-scale Evaluations…**	
11:00 AM	Discriminating Explosions From Earthquakes and Collapses With Seismic and Acoustic Waves. **Walter, W. R.**, Pyle, M., Ford, S. R., Pitarka, A., Kong, Q., *et al.*	The Importance of Induced Seismicity Monitoring to De-risk Geothermal EGS Projects. **Savvaidis, A.**, Taff, C., O'Sullivan, V., Shirley, M.	STUDENT: Lateral Variations of Crustal Lg-wave Attenuation in and Around the Scandinavian Peninsula. **Liu, Z.**, Zhao, L., Xie, X., Yao, Z.	
11:30 AM–12:30 PM	*Plenary:* Science and Technology from a Makah Perspective—Incorporation of Native American Knowledge Systems			
12:30–2:00 PM	Lunch Break			

Time	Grand A	Grand B	Grand C	Grand E–K*
	Fault Damage Zones: What We Know and Do Not (see page 1276).	**Using Data and Experience to Improve Geohazards Communication** (see page 1359).	**Advances in Geospatial Modeling of Seismic Hazards** (see page 1220).	**What Controls the Style of Fault Slip in Subduction Zones?** (see page 1360).
2:00 PM	INVITED: Seismic Imaging of the Mw 7.1 Ridgecrest Earthquake Rupture Zone and Garlock Fault From Data Recorded by Dense Linear Arrays. **Qiu, H.**, Chi, B., Ben-Zion, Y.	Earthquake Science Communication in Stable Continental Regions. **Pascale, A.**	Nowcasting Earthquakes with Machine Learning: The Role of Strain Hardening in the Earthquake Cycle with Implications for Slow and Silent Slip Events and Current Earthquake Hazard. **Rundle, J. B.**, Yazbeck, J., Donnellan, A., Fox, G., Grant Ludwig, L., *et al.*	Insights Into the Occurrence and Characteristics of Near-trench of Slow Slip Events at the Hikurangi Subduction Zone From Some Recent Seafloor Geodetic Experiments and IODP Observatories. **Wallace, L. M.**, Ito, Y., Saffer, D., Davis, E., Palmer, N., *et al.*
2:15 PM	Tomography of the Ridgecrest Fault Region Using Aftershocks as a Network of Virtual Seismometers. **Matzel, E.**	Impact of the National Seismological Service (Mexico) Outreach Activities. **Pérez-Campos, X.**, Cardenas Monroy, C., Vela Rosas, M. A., Sosa Jiménez, M. A., Ruiz, I., *et al.*	STUDENT: Development of Geospatial Liquefaction Probability Models for M5.4 Pohang Earthquake, South Korea. **Seo, H.**, Kim, H., Kim, B.	INVITED: STUDENT: Can Stochastic Modeling Capture Slip Distributions for M9 Events? **Small, D. T.**, Melgar, D., Lin, J.
2:30 PM	STUDENT: Ambient Noise Tomography of the Ridgecrest Fault Damage Zones: What We Know and Do Not. **Zhou, Z.**, Gerstoft, P., Bianco, M. J., Olsen, K. B.	A Decade of Creating Data Visualizations for Online Video Content: The Pacific Tsunami Warning Center's Earthquake and Tsunami Animations. **Becker, N. C.**, Wang, D., Geschwind, L. R., Fryer, G. J., Preller, C. C., *et al.*	Determination of Coseismic Landslide Hazard Using Physics-based Ground-motion Simulation: Application for the 2021 Haiti Earthquake. **Castro-Cruz, D.**, Aquib, T., Lombardo, L., Tanyas, H., Mai, P.	What Makes Low-frequency Earthquakes Low Frequency: Cluster-based Constraints on the Attenuation Structure of the Nankai Plate Interface, Japan. **Wang, Q.**, Frank, W. B., Abercrombie, R. E.

Time	Cedar*	Regency A–C	Regency E–G
	Tectonics and Seismicity of Intraplate Regions	**Numerical Modeling in Seismology…**	**50-State Update of the USGS National Seismic Hazard Models**
11:00 AM	Buried Basement Faults Posing Potential Seismic Risk in South Carolina: Insights From High-resolution Aeromagnetic Data. **Shah, A. K.**, Pratt, T. L., Horton, Jr., J.	Seismic Response of Metamaterials Using the Indirect Boundary Element Method for SH Waves in 1D and 2D. **Piña-Flores, J.**, Perton, M., Goh, H., Kallivokas, L. F., Sánchez-Sesma, F. J.	Paleoseismological Perspectives on Megathrust Locking, Rupture and Tsunami Hazard in Alaska. **Witter, R. C.**, Briggs, R. W., Dura, T., Engelhart, S. E., Nelson, A., *et al.*
11:30 AM–12:30 PM	*Plenary:* Science and Technology from a Makah Perspective—Incorporation of Native American Knowledge Systems		
12:30–2:00 PM	Lunch Break		

Time	Cedar*	Regency A–C	Regency E–G
	The Effects of Sedimentary Basins on Earthquake Ground Motions (see page 1263).	**Tectonics and Seismicity of Intraplate Regions** (see page 1349).	**50-State Update of the USGS National Seismic Hazard Models** (see page 1193).
2:00 PM	INVITED: Impacts of Seattle Basin on Performance of RC Core-wall Buildings During M9 Cascadia Subduction Zone Earthquakes. **Eberhard, M. O.**, Marafi, N. A., Berman, J. W., Wirth, E. A., Frankel, A. D.	Seismicity of Elysium Planitia, Mars. **Stähler, S. C.**, Mittelholz, A. M., Perrin, C., Jacobs, A., Kawamura, T., *et al.*	INVITED: Updates to the Ground-motion Characterization for the 2023 US National Seismic Hazard Model. **Moschetti, M. P.**, Aagaard, B. T., Ahdi, S. K., Boyd, O. S., Petersen, M. D., *et al.*
2:15 PM	STUDENT: Evaluation of Source and Basin-induced Surface Waves on Seismic Performance of Non Linear Structures. **Soto, V.**, Lopez-Caballero, F.	Seismic Imaging of the Ups and Downs of the North American Midcontinent. **Yang, X.**, Liu, L., Stevens Goddard, A.	Assessment of Western US Basin Response and Implementation in the 2023 Update of the US National Seismic Hazard Model. **Ahdi, S. K.**, Moschetti, M. P., Aagaard, B. T., Boyd, O. S., Frankel, A. D., *et al.*
2:30 PM	Monitoring the Compaction Underneath Mexico City Using Ambient Noise. **Ermert, L. A.**, Denolle, M. A., Solano Rojas, D., Cabral Cano, E., Chaussard, E., *et al.*	STUDENT: Seismic Observations of Complex Mantle Transition Zone Structure Beneath Eastern North America. **Burky, A. L.**, Irving, J. C. E., Simons, F. J.	Probabilistic Seismic Hazard Analysis in Seattle Using Non-ergodic GMMs Based on 3D Simulation Results for Cascadia Interface Earthquakes. **Sung, C.**, Abrahamson, N.

Time	Grand A	Grand B	Grand C	Grand E–K*
	Fault Damage Zones…	**Using Data and Experience…**	**Advances in Geospatial Modeling…**	**What Controls the Style of Fault Slip…**
2:45 PM	STUDENT: Using Active Source Seismology to Image a Strike-slip Fault Damage Zone as a Function of Depth, Distance and Geology. **Alongi, T.**, Brodsky, E. E., Kluesner, J., Brothers, D. S.	Communicating ShakeAlert® with an Online, Educational Animation: Project Overview and Preliminary Evaluation Results. **Crayne, J.**, Herran, C., Sumy, D. F.	A Geospatial Model for Site Response Complexity. **Zhan, W.**, Baise, L. G., Kaklamanos, J.	STUDENT: CASIE21 Seismic Reflection Images Reveal Potentially Active Splay Faulting at Dynamic Backstop in Cascadia Accretionary Wedge. **Lucas, M. C.**, Tobin, H., Carbotte, S. M., Han, S., Boston, B.
3:00 PM	STUDENT: Fault Damage Zone Effects on Near-field Ground Motions in a Multi-scale Dynamic Rupture Model of the 2019 Ridgecrest Sequence. **Schliwa, N.**, Gabriel, A., Taufiqurrahman, T.	Assessment of the General Public's Understanding of Rapidly Produced Earthquake Information Products Shakemap and Pager. **Brudzinski, M. R.**, Karjack, S., Shipley, T.	STUDENT: A US National Vs30 Model and Map Driven by Remote Sensing and Machine Learning. Maurer, B. W., **Geyin, M.**	Unsteady, Uniform Rupture Growth Revealed by Tectonic Tremors in Cascadia. **Wech, A.**, Gomberg, J.
3:15 PM–4:30 PM	Poster Break			
	Fault Damage Zones: What We Know and Do Not (see page 1276).	**Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination** (see page 1295).	**Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage** (see page 1292).	
4:30 PM	INVITED: Acceleration and Coalescence of Damage Zone Seismicity Leading Up to Large Earthquakes. **Cattania, C.**	Web Interfaces and Web Services for Open Coordinated Strong-motion Data Dissemination in Europe. **Lanzano, G.**, Cauzzi, C., Bienkowski, J., Bindi, D., Cakti, E., *et al.*	Multiplet Analysis for Identification of Fractures in Areas of Fluid Migration: A Comparative Study of Seismicity Clusters From the Geysers Geothermal Field, California and Song Tranh 2 Water Reservoir, Vietnam. **Staszek, M.**, Rudziński, L., Kwiatek, G., Lizurek, G., Orlecka-Sikora, B.	
4:45 PM	Fault Roughness and Frictional Stability Control Seismic Energy Partitioning Between Fore, Main and Aftershocks During Laboratory Stick-slip. **Goebel, T. H. W.**, Dresen, G.	Identifying Strong-motion Instrument Metadata Inconsistencies Before and After Earthquakes. **Schleicher, L. S.**, Steidl, J. H., Brody, J., Blair, L., De Cristofaro, J. L., *et al.*	Supervised and Unsupervised Machine Learning Applications for Induced Seismic Data Analysis at Illinois Basin Decatur Project Site. **Yoon, H.**, Lizama, D., Willis, R.	

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	The Effects of Sedimentary Basins on Earthquake Ground Motions	**Tectonics and Seismicity of Intraplate Regions**	**50-State Update of the USGS National Seismic Hazard Models**
2:45 PM	STUDENT: Analysis of Rayleigh Waves in the Sedimentary Basin of Bogotá, Colombia. **Daza, J. M.**, Soto, V., Riaño, A., Lopez-Caballero, F., Reyes, J. C.	Aftershock Sequences in Central/ Eastern North America Last Years—Decades at Most—Not a Few Weeks, Not Millennia: Results From 149 Modern Mainshocks mw3.65–5.84. **Levandowski, W.**	STUDENT: A Ground-motion Prediction Model for Induced Earthquakes for Central and Eastern United States. **Farajpour, Z.**, Pezeshk, S.
3:00 PM	Ground Motion Time Histories for Subduction Zone Earthquakes Using Artificial Intelligence. **Florez, M. A.**, Ross, Z. E., Asimaki, D.	Refinements to the Bayesian Approach for the Calculation of Maximum Earthquake Magnitude (Mmax) in Stable Continental Regions. **Toro, G. R.**	Exploring Potential Implications to Engineering and Risk Applications From Including Epistemic Uncertainties in Hazard for the USGS 2023 NSHM. **Kwong, N. S.**, Jaiswal, K. S.
3:15 PM–4:30 PM	Poster Break		
	The Effects of Sedimentary Basins on Earthquake Ground Motions (see page 1263).	**Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information** (see page 1305).	**What Controls the Style of Fault Slip in Subduction Zones?** (see page 1360).
4:30 PM	STUDENT: Sediment-basement Structure of the Northern Los Angeles Basins. **Villa, V.**, Li, Y., Ghose, R., Clayton, R. W., Persaud, P.	Enhanced Rapid Earthquake Ground Failure and Impact Estimates With Remotely Sensed and Ground Truth Constraints. **Wald, D. J.**, Xu, S., Noh, H., Dimasaka, J. T., Jaiswal, K. S., *et al.*	Empirical Low-frequency Earthquakes Synthesized From Tectonic Tremor Records. **Ide, S.**
4:45 PM	STUDENT: Shear Wave Velocity Model for the San Gabriel and San Bernardino Basins From Dense-array Ambient Noise Correlation. **Li, Y.**, Villa, V., Ghose, R., Clayton, R. W., Persaud, P.	Local-international Collaboration Following the 2021 Haiti Earthquake for Rapid Building Damage Data Collection and Public Awareness Messaging. Rodgers, J., Kijewski-Correa, T., Presuma, L., McBride, S. K., Devilme, G., Mentor-William, G., Lochhead, M., Canales, E., Mbabazi, A., **Stenner, H.**, *et al.*	Widespread Very Low Frequency Earthquakes (VLFEs) Offshore Cascadia. **Ghosh, A.**, Chaudhuri, K.

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Fault Damage Zones: What We Know…	**Improving Strong-motion Data…**	**Imaging, Monitoring and Induced Seismicity…**	
5:00 PM	A Geodetic Constraint on Seismic Velocity Changes in Fault Damage Zones. **Xu, X.**, Liu, D., Lavier, L., Sandwell, D. T.	Improving the Development Pipelines for USGS Earthquake Hazards Program Real-time and Scenario Products. **Aagaard, B. T.**, Wald, D. J., Thompson, E. M., Hearne, M., Schleicher, L. S.	INVITED: Coupling Induced Seismicity to Permeability Using Spatial Correlation Analysis of EGS Data. **Malin, P. E. A.**, Leary, P. C.	
5:15 PM	Fault Friction Derived from Fault Bend Influence on Coseismic Slip During the 2019 Ridgecrest Earthquake. **Milliner, C. W. D.**, Aati, S., Avouac, J.	STUDENT: Systematic Quality Control of National Strong Motion Project Structure Instrumentation Using Teleseismic Data. **Heilpern, K. A.**, Schleicher, L. S., Steidl, J. H., Gee, L. S.	INVITED: It's in the Eye of the Beholder: Previously Discarded Seismic Noise May Tell Us Just as Much About Anthropogenic Fluid Injection as Detected Earthquakes. **Salvage, R. O.**, Eaton, D. W.	
5:30 PM	STUDENT: 738,000 Years of Off-fault Damage at the Volcanic Tablelands. **Rodriguez Padilla, A. M.**, Oskin, M. E.	STUDENT: Uncertainty Quantification Over Spectral Estimation of Ground Motion Processes Subject to Missing Data Using Variational Bayesian Inference. **Chen, Y.**, Patelli, E., Edwards, B., Beer, M.	Activation of Optimally and Unfavorably Oriented Faults Within the Oklahoma LASSO Nodal Array. **Pennington, C. N.**, Skoumal, R. J., Rubinstein, J. L.	
6:00 PM–7:00 PM	*Plenary:* The Future of Subduction Zone Science			
7:00 PM–8:00 PM	Early-Career & Student Reception			

Poster Sessions

Numerical Modeling in Seismology: Developments and Applications (see page 1323).

1. STUDENT: Investigation of Lithospheric Structure in NE India Based on Love Wave Data. **Chanu, N.**, Kumar, N., Mukhopadhyay, S.
2. STUDENT: Efficient Quasi-dynamic Simulations of Earthquakes and Aseismic Slip Including Off-fault Viscoelastic Deformation Using Hierarchical Matrices. **Wick, J. M.**, Lambert, V.
3. STUDENT: A New Approach to Estimate a Mixed Model-based Ground-motion Model Using a Computational Optimization Algorithm. **Akhani Senejani, M.**, Pezeshk, S.
4. Simulation of Mw 7 2016 Kumamoto Earthquake Mainshock Using Dynamic Rupture Modeling. **Sun, J.**, Pitarka, A., Kawase, H., Nagashima, F., Ito, E.
5. An Efficient ADER-DG Scheme for Simulation of Seismic Waves in Poroelastic Media. Wolf, S., **Galis, M.**, Uphoff, C., Gabriel, A., Moczo, P., *et al.*

Adjoint Waveform Tomography: Methods and Applications (see page 1202).

6. STUDENT: Seismic Wavefield Simulations of 3D Anisotropy in a Mantle Wedge Setting. **Gupta, A.**, Tape, C., Abers, G. A.
7. Finite-frequency Kernels for Pg Phases. **Nelson, P.**, Modrak, R., Phillips, W., Begnaud, M.
8. STUDENT: Full 3D Fréchet Kernels for Low-frequency Slowness Perturbations Measured Across Seismic Arrays. **Vazquez, L.**, Jordan, T. H.
9. STUDENT: Scattered Wave Imaging of Lithospheric Discontinuities: Eliminating Moho Reverberations With Radon Filters. **Carr, S. A. B.**, Olugboji, T.

Time	Cedar*	Regency A–C	Regency E–G
	The Effects of Sedimentary Basins on Earthquake Ground Motions…	**Modeling, Collecting and Communicating…**	**What Controls the Style of Fault Slip in Subduction Zones?**
5:00 PM	Effects of the Los Angeles Basin on Ground Motion Studied Using Lab Experiments on a 3D-printed Model. **Wang, J.**, Park, S.	NASA Urgent Response Products for the 2021 Mw 7.2 Earthquake in Haiti. Fielding, E. J., Jung, J., Amatya, P., Huang, M., Bato, M., **Handwerger, A.**, Emberson, R.	Analysis of Eight-year-long Low-frequency Earthquake Catalog for Southern Cascadia. **Creager, K.**, Ducellier, A.
5:15 PM	INVITED: Broadband Ground Motion Simulations with Sediment Nonlinearity: A Case Study at Garner Valley, California. **Seylabi, E.**	Best Practices for Collecting and Using Post-earthquake Damage Data: Lessons from Haiti and Other Past Events. **Loos, S.**, Lallemant, D., Wald, D. J.	Emergence of Repeating Earthquakes Along the Mexican Subduction. **Dominguez, L. A.**, Taira, T., Cruz-Atienza, V. M., Iglesias, A., Legrand, D., *et al.*
5:30 PM	Verification and Validation of the Broadband Cybershake Platform Using Observations. **Callaghan, S. A.**, Goulet, C. A., Silva, F., Maechling, P. J., Graves, R. W., *et al.*	STUDENT: Improving the USGS Pager System's Reported Fatality Updating Framework. **Engler, D. T.**, Jaiswal, K. S., Wald, D. J.	Time-domain Source Parameter Estimation of Mw3-7 Earthquakes in Japan. **Yoshida, K.**, Kanamori, H.
6:00 PM–7:00 PM	*Plenary:* The Future of Subduction Zone Science		
7:00 PM–8:00 PM	Early-Career & Student Reception		

10. STUDENT: The Effect of Mantle Corrections on SmKS Measurements. **Vite Sanchez, R.**, Bozdag, E., Frost, D. A., Creasy, N.
11. STUDENT: Observations of Inner Core Shear Waves With AlpArray. **Ling, A.**, Stähler, S. C., Kim, D., Giardini, D.

Advancing Multi-scale Evaluations of Seismic Attenuation (see page 1237).

12. Spatial Variability of the Spectral Decay Parameter Kappa and Near-source Attenuation in Central Italy. **Castro, R. R.**, Colavitti, L., Vidales-Basurto, C. A., Pacor, F., Sgobba, S., *et al.*
13. Including Radiation Pattern Effects in Ground-motion Models for Taiwan. Huang, J., **Sung, C.**, Chao, S., Abrahamson, N.
14. Computing Path Effects of a Large Magnitude Event From Path Effects of Many Small Magnitude Events on the Same Rupture Plane. **Meng, X.**, Goulet, C. A.
15. The Eastward Expansion of the Eastern Tibetan Plateau Inferred From Stress Drops of the 2021 Ms 6.4 Yangbi Earthquake in Yunnan and the Ms 7.4 Maduo Earthquake in Qinghai, China. **He, X.**, Zhao, L., Xie, X., Zhang, L., Yao, Z.
16. STUDENT: Pn-wave Attenuation Structure of the Uppermost Mantle Beneath the Japan Sea. **Yang, G.**, Zhao, L.
17. STUDENT: Spatiotemporal Variation of Stress Drop for the 2019 ML 6.0 Changning Earthquakes and Its Aftershock Sequence in the southern Sichuan Basin, China. **Shen, L.**, Zhao, L., Xie, X., He, X., Wang, W., *et al.*
18. Examining Temporal Variations in Coda Q Attenuation Before and After Some Significant Canadian Earthquakes: The 2017 Resolute Earthquake (Mw 6.1) in Nunavut, Canada. Farahbod, A., **Cassidy, J. F.**

Advances in Geospatial Modeling of Seismic Hazards (see page 1221).

19. OpenAmp: A Global Seismic Site Amplification Database. **Zhu, C.**, Loviknes, K., Kotha, S., Bora, S., Cotton, F.
20. Geospatial Mapping of Seismic Hazards: An Example of Site Amplification Mapping in the New Madrid Seismic Zone of Central United States. **Wang, Z.**, Carpenter, S., Zhu, Y.
21. Exploring the Potential for SAR Phase to Capture Soil Moisture Variability to Improve Earthquake-triggered Ground Failure. **Burgi, P. M.**, Thompson, E. M., Allstadt, K. E., Lohman, R. B., Collins, B.
22. NSF SAGE-facility Begins Procurement of Rapid Response Instrumentation. **Sweet, J. R.**, Anderson, K., Meltzer, A., Woodward, B.
23. Student: Evaluating Machine Learning Methods Applied To Physics-based Ground Motion Modeling via Proper Orthogonal Decomposition. **Rekoske, J. M.**, Gabriel, A., May, D.
24. Student: Geology and Geomorphology Based f0 Model of New England. **Pontrelli, M. A.**, Baise, L. G., Ebel, J. E., Mabee, S. B., Zhan, W.
25. Ground-motion Modeling Using Machine Learning Techniques and Geospatial Proxies. **Zhan, W.**, Baise, L. G., Kaklamanos, J.
26. Student: Global Geospatial Liquefaction Model Updates Using Advanced Machine Learning Algorithms. **Asadi, A.**, Baise, L. G., Chatterjee, S., Chansky, A. A.
27. Student: Updated Global Geospatial Liquefaction Model Using Logistic Regression. **Akhlaghi, A. M.**, Chansky, A. A., Baise, L. G., Moaveni, B.

Tectonics and Seismicity of Intraplate Regions (see page 1353).

28. Student: The Seismicity of West Africa: Construction of a Focal Mechanism Catalog with a Sparse Dataset. **Legre, J. B.**
29. Active Tectonics of the Central Adriatic Region: New Insights from the Recent March 2021 Seismic Sequence (Mw5.2). **Di Luccio, F.**, Marchetti, A., Dannowski, A., Dasović, I., Gasperini, *et al.*
30. Mapping the m5.8 Mineral Earthquake Aftershock Sequence and the Virginia Seismic Zone. Aden, F., **Frank, W. B.**, Abercrombie, R. E.
31. High-resolution Receiver Function Analysis of the Pecos, Texas Region. Veitch, M. A., **Karplus, M.**, Chaput, J.
32. Student: Joint Inversion of HVSR and Surface Wave Group Velocity Dispersion to Characterize Shallow Sediments at the Monahans Dune Field, West Texas. **Spears, B.**, Pulliam, J. R.
33. Delineating the Crustal Seismic Attenuation Boundary Between the Central/Eastern and Western United States. **Levandowski, W.**, McNamara, D. E.
34. The 2021 Milford, UT Earthquake Swarm. **Whidden, K. M.**, Mesimeri, M., Pankow, K. L.
35. Student: A Comparison of Three Modern Aftershocks Sequences Across Southern Idaho: Characterizing the Seismogenic Zone Surrounding the Snake River Plain. **Wilbur, S. F.**

Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information (see page 1306).

41. Towards Developing and Implementing an International Macroseismic Scale (IMS) for Earthquake Engineering, Earthquake Science and Rapid Damage Assessment. **Wald, D. J.**, Goded, T., Hortacsu, A., Spence, R., de Rubeis, V., *et al.*
42. Student: Updating Liquefaction Probability Given Liquefaction Potential Index in a Bayesian Framework. **Engler, D. T.**, Thompson, E. M., Geyin, M., Maurer, B. W., Jaiswal, K. S., *et al.*
43. Advancing Real-time Tsunami Warning and Response: From Characterizing the Hazard Using GNSS to Estimating Loss Models. **Kwong, K.**, Crowell, B. W., Melgar, D., Eguchi, R., Esquivias, G., *et al.*
44. Student: A Feature-based Liquefaction Image Dataset for Assessing Liquefaction Extent and Impact. **Sanon, C.**, Baise, L. G., Asadi, A., Koch, M., Aimaiti, Y., *et al.*

Using Data and Experience to Improve Geohazards Communication (see page 1360).

45. Student: GeoGateway for Higher Level Analysis and Visualization of Data. Mirkhanian, M. A., **Grant Ludwig, L.**, Donnellan, A., Pierce, M., Wang, J., *et al.*

Diversity, Equity and Inclusion in Seismology (see page 1251).

46. A Summary of Existing Resources and Roadmap for the Hazards Equity Working Group of the American Geophysical Union's Natural Hazards Section. **Hobbs, T. E.**, Sumy, D. F., Tepp, G., Flanagan, M. P., Kakoty, P., *et al.*
47. Working To Ensure a More Diverse, Equitable, Inclusive and Accessible Workplace: DEIA Actions Within the US Geological Survey's Alaska Region. **Moran, S. C.**, Devaris, A. M., Deligne, N. I., Ellis, A. P., Flinders, A. F., *et al.*

From Desktops to HPC & Cloud: Emerging Strategies in Large-scale Geophysical Data Analysis (see page 1284).

48. Student: Efficient Access and Manipulation of Big Seismic Data from Disparate Sources. Dugda, M., **Kassa, A. B.**, Pouchard, L., Dires, E., McDaniel, L.
49. Implementing Cloud-optimized Geophysical Data Containers. **Berglund, H. T.**
50. HDF5eis: A Solution for Storing and Accessing Big, Multidimensional Data From Environmental Sensors. **White, M. C. A.**, Nakata, N.

Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination (see page 1296).

51. Student: A Python-based Toolset for Identifying Strong-motion Earthquake Database Gaps. **Shao, H.**, Brody, J., Schleicher, L. S., Gee, L. S., Steidl, J. H.
52. Ground Motion Packet (GMP): A GeoJSON Specification for Ground Motion Metrics. Yu, E., Hagos, L., Steidl, J. H., **Thompson, E. M.**, Worden, C. B.
53. Systematic Comparisons of Broad-band Velocity and Acceleration Earthquake Records as a Quality Assessment Tool for European Open Strong-motion Data. **Cauzzi, C.**, Bindi, D., Cambaz, D., Carrilho, F., Custódio, S., *et al.*
54. Güralp Data Centre Software for Easy Mass Data Acquisition and Station Metadata Monitoring. **Lindsey, J. C.**, Reis, W., Watkiss, N., Hill, P., Cilia, M.
55. A DesignSafe Ground Motion Database. **Ji, C.**, Cabas, A., Kottke, A., Pilz, M., Macedo, J., *et al.*

Advances in Geophysical Sensing (see page 1217).

56. Inference of the Relative Strain Energy Density of Compressional and Shear Waves Using Seismic Gradiometer. **Poppeliers, C.**, Berg, E. M., Young, B.
57. Evaluating the A-0-A Method for In-situ Calibration of Seafloor Pressure Gauges at Axial Seamount. **Wilcock, W. S. D.**, Manalang, D. A., Fredrickson, E., Sasagawa, G. S., Zumberge, M., *et al.*
58. Infrasound Direction-of-arrival Determination Using a Balloon-borne Aeroseismometer. **Bowman, D. C.**, Rouse, J. W., Sinclair, A. M., Silber, E. A., Krishnamoorthy, S.
59. The Next Generation Compact Broadband Seismometer: Güralp Certis. **Lindsey, J. C.**, Reis, W., Watkiss, N., Hill, P., Cilia, M.
60. Improved Resolution Across the Global Seismographic Network: A New Era in Low-frequency Seismology. Ringler, A. T., **Anthony, R. E.**, Davis, P., Ebeling, C., Hafner, K., *et al.*
61. Student: Results From a Novel Self-calibrating Tiltmeter at Axial Seamount. **Fredrickson, E.**, Wilcock, W. S. D., Harrington, M. J., Cram, G. S., Tilley, J.
62. Seismic Data Acquisition for Portable Deployments—A New and Transformative Approach. Easton, D., Perlin, M., Pigeon, S., Parker, T., Pelyk, N., **Bainbridge, G.**
63. Next Generation Regional Arrays for Strong and Weak Motion Using Cascadia 120 Slim Posthole. **Bainbridge, G.**, Parker, T., Wuthrich, D., Pelyk, N.
64. Recent Improvements in Very Broadband Seismometer Self-noise Performance Embodied in the New Trillium 360 GSN Instruments. **Bainbridge, G.**, Townsend, B., Upadhyaya, S., Pelyk, N.
65. Digital Low-noise Optical Seismic Sensor. **Avenson, B.**
66. Student: In-situ Measurement of Modal Rotations at a Freestanding Rock Tower. **Dzubay, A.**, Moore, J. R., Finnegan, R., Bessette-Kirton, E. K., Geimer, P. R., *et al.*
67. Towards Installing a Very Broadband Seismometer 2.4 Km Below the Surface at South Pole, Antarctica. **Anthony, R. E.**, DuVernois, M., Ringler, A. T., Cherwinka, J., Jones, D. K., *et al.*

Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources (see page 1357).

68. Student: A Major Update to the Exotic Seismic Events Catalog: A Compilation of Seismogenic Mass Movements. Collins, E., **Allstadt, K. E.**, Groult, C., Hibert, C., Malet, J., *et al.*
69. Detecting Landslides in the Barry Arm Region Using Long-period Signals. **Karasozen, E.**, West, M. E.
70. Student: Spatio-temporal Variation of Ambient Noise in the Sikkim Himalaya. **Uthaman, M.**, Singh, C., Singh, A., Jana, N., Dubey, A. K., *et al.*
71. Student: Variations in Ambient Seismic Noise of the California Central Coast. **Shabtian, H. S.**, Eilon, Z.
72. Student: Variability and Precision of Acoustic-to-seismic Coupling from Explosions Recoded Across Albuquerque Seismological Laboratory. **Watzak, J. M.**, Anthony, R. E., Ringler, A. T., Wilson, D. C.
73. Arrival Time Based Seismoacoustic Source Location Using a Bayesian Framework. **Koch, C.**, Dannemann Dugick, F. K., Berg, E. M., Blom, P.
74. Student: Refining First-arrival Traveltime Picks of Active Seismic Data for Improving Structure Characterization at Rock Valley, Nevada. **Li, D.**, Huang, L., Chen, T., Gao, K., Snelson, C., *et al.*
75. Regional Moment Tensor Inversion of the Western United States Using a Three-dimensional Earth Model. **Chiang, A.**, Rodgers, A., Krischer, L., Afanasiev, M., Boehm, C., *et al.*

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances (see page 1245).

76. Student: Using the 2009 Basel Enhanced Geothermal Systems Project as a Proxy for Predicting Reservoir Development at Utah Forge. **Bradshaw, P.**, Dyer, B., Bethmann, F., Dzubay, A., Petersen, G., *et al.*
77. Similar Event Clusters and Microseismic Event Relocation at the Utah Forge Site. **Ratre, P.**, Chen, X.
78. Using Machine Learning for Characterizing Induced Microseismics at the Forge Geothermal Site. Shi, P., **Lanza, F.**, Grigoli, F., Wiemer, S.
79. Building a Probabilistic Seismic Hazard and Risk Model for EGS Stimulations. **Grigoratos, I.**, Papadopoulos, A. N., Ciardo, F., Rinaldi, A. P., Lanza, F., *et al.*
80. Compact Broadband Instrumentation for Geothermal Field Monitoring. **Lindsey, J. C.**, Reis, W., Watkiss, N., Hill, P., Cilia, M.
81. Student: Insights Into Hydraulic Fracturing Processes From Waveform-similarity Analyses of Acoustic Emissions Induced in Mine-scale Experiments. **Niemz, P.**, Petersen, G., Cesca, S., Dahm, T., Zang, A.
82. Ambient Noise-based Monitoring of Seismic Wave Velocity Modulations at the Carbfix Reinjection Site, SW-Iceland. **Qiu, H.**, Nakata, N., Pec, M., Sánchez-Pastor, P., Obermann, A.

Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage (see page 1293).

83. Exploring the Role of Wastewater Disposal in Causing Recent Increases in Seismicity in Central and Northern Kansas. **Fasola, S. L.**, Barlow, N. M., Brudzinski, M. R.
84. Detecting Fluid Movement in Seismogenic Faults Using Earthquake Attributes in Oklahoma. **Ogwari, P. O.**, Walter, J., Woelfel, I., Thiel, A., Ferrer, F.
85. Diverse Fault Architectures and Stress States Evolutions of Induced Earthquake Sequences Revealed by High-resolution Focal Mechanism Solutions. Qin, Y., **Chen, X.**, Chen, T., Abercrombie, R. E.
86. Student: A Strategy for Choosing Red-light Thresholds to Manage Hydraulic Fracturing Induced Seismicity in North America. **Schultz, R.**, Beroza, G. C., Ellsworth, W. L.
87. Fault Activation by Induced Aseismic Slip: Scaling Behaviour and New Observations. Eaton, D. W., Eyre, T., Wang, C., Ma, Y., **Salvage, R. O.**
88. Improving the Catalog of Induced Seismicity in Southeastern New Mexico. **Litherland, M.**, Huang, G.

Observations and Modeling of the 2021 Haiti Earthquake (see page 1324).

89. Landslides Triggered by the 14 August 2021, Magnitude 7.2 Nippes, Haiti, Earthquake. Martinez, S. N., **Allstadt, K. E.**, Slaughter, S. L., Schmitt, R., Collins, E., *et al.*
90. Limitations of a Teleseismic-only Dataset for 2021 mw7.2 Nippes, Haiti, Finite Fault Modeling: Improved Modeling Capability for Joint Teleseismic and Regional Inversion. **Goldberg, D. E.**, Koch, P., Melgar, D., Riquelme, S., Yeck, W. L., *et al.*
91. Slip in the 14 August Haiti Earthquake Derived From InSAR and Pixel Offsets. **Maurer, J.**, Dutta, R., Vajedian, S., Lee, Y.

Searching for Fault Creep Over a Range of Timescales (see page 1331).

92. Student: Are Creep Events Big? Estimations of the Along-strike Rupture Extent of Creep Events Along the Central San Andreas Fault. **Gittins, D. B.**, Hawthorne, J. C.
93. Investigation of Fault Creep Variability Along the Southern San Andreas Fault. **Liu, Z.**, Luo, Y., Lundgren, P.
94. Interseismic and Postseismic Creep Detected From Five Years of Sentinel-1 InSAR Data Over Northeastern Tibetan Plateau. **Ou, Q.**, Daout, S., Parsons, B., Wright, T.
95. Seismic and Aseismic Fault Slip During the Inter-seismic Period: Observations From the Marmara Region of the North Anatolian Fault. **Martinez-Garzon, P.**, Becker, D., Durand, V., Kwiatek, G., Bohnhoff, M., *et al.*
96. Student: Assessing Thermal and Hydrologic Conditions of Fault Creep in the Salton Trough From the Exhumed Sedimentary Section of the Fish Creek-Vallecito Basin. **Young, E. K.**, Oskin, M. E., Stockli, D. F., Chatterjee, R.
97. The Search for Dynamically Triggered Changes in Plate Interface Coupling and Implications for Fault Coupling Models. **Bartlow, N. M.**
98. A Comprehensive Catalog of Repeating Earthquakes for Northern California: Implications for Fault Creep, Slip Rates, Slip Partitioning and Transient Stress. **Waldhauser, F.**, Schaff, D. P.

Exploring Earthquake Source Dynamics and Wave Propagation Properties in Tectonic and Lab Environments (see page 1271).

99. Invited: Temporal Variation of Qc and Its Implications in Medium Characterization. **Gupta, S. C.**, sharma, M. L., Jain, S., Sen, A., Jindal, A., *et al.*
100. Student: Probabilistic Constraints on the Southern Californian Seismic Energy Budget From Heat Flow

Across the San Andreas Fault. **Ziebarth, M. J.**, Anderson, J. G., von Specht, S., Heidbach, O., Cotton, F.

101. Student: Ground Motion Prediction Models for Pennsylvania From Industrial Seismic Sources. Deane, C., Ammon, C. J., **Kintner, J.**
102. Student: Characteristics of Pulse Duration and Amplitude of P-wave Seismograms. **Heo, Y.**, Lee, J., Kim, B.
103. Fully-automated Processing of Single- and Multi-peak Microtremor HVSR Measurements Using Machine Learning. **Vantassel, J. P.**
104. Student: Mapping Active Faulting in Post-mining Induced Seismicity by Network-based Waveform Similarity Analyses and Moment Tensor Inversions. **Niemz, P.**, Namjesnik, D., Cesca, S., Kinscher, J., Contrucci, I., *et al.*
105. Student: Radiation-pattern Effects in Bay Area Ground-motion Models. **Liou, I. Y.**, Abrahamson, N.

What Controls the Style of Fault Slip in Subduction Zones? (see page 1363).

106. Student: Slow Slip Dynamics Reproduced by Symptomatic Low-frequency Earthquake Activity. **Mouchon, C.**, Frank, W. B., Radiguet, M., Poli, P., Cotte, N.
107. Nature of the Volcanic Upper Crust of the Hikurangi Plateau: Implications for Megathrust Structure and Hydrogeology. **Gase, A. C.**, Bangs, N., Han, S., Kodaira, S., Arai, R., *et al.*
108. Student: Tectonic Tremor Localization Using Bayesian Inversion. **Bombardier, M.**, Cassidy, J. F., Dosso, S. E., Kao, H.
109. Student: Triggering Dynamics of Tremor-like Events During Laboratory Hydrofracturing. **Yuan, C.**, Cochard, T., Ulberg, C., Denolle, M. A., Creager, K., *et al.*

50-State Update of the USGS National Seismic Hazard Models (see page 1197).

110. Update on the Implementation of Seismic Directivity Models Into the USGS National Seismic Hazard Model. Withers, K. B., **Moschetti, M. P.**, Thompson, E. M., Frankel, A. D., Wirth, E. A., *et al.*
111. Investigating the Effects of Declustering Choices on Probabilistic Seismic Hazard Assessments. **Llenos, A.**, Michael, A. J.
112. Hybrid Empirical Ground-motion Models With Simulation-based Site Amplification Factors for the Island of Hawaii. Pezeshk, S., **Haji-Soltani, A.**
113. Student: Determination of Seismological Parameters in Central and Eastern North America. Pezeshk, S., **Assadollahi, C.**, Zandieh, A.
114. Revised Earthquake Geology Inputs for the Central and Eastern United States and Southeast Canada for the 2023 National Seismic Hazard Model Update. **Jobe, J. A. T.**, Hatem, A. E., Gold, R., DuRoss, C. B., Reitman, N., *et al.*
115. Western US Geologic Deformation Model for Use in the US National Seismic Hazard Model 2023. **Hatem, A. E.**, Briggs, R. W., Gold, R., Reitman, N., Jobe, J. A. T., *et al.*
116. A New Alaska-Aleutian Subduction Zone Rupture Model for Use in the National Seismic Hazard Model. **Briggs, R. W.**, Witter, R. C., Ross, S., Freymueller, J. T., Thio, H.
117. The Potential Impact of Listric Faults on the National Seismic Hazard Maps. **Wong, I. G.**, Thomas, P., Pechmann, J. C.
118. Student: Investigation and Re-calculation of TL: The Long-period Transition Parameter. **Assadollahi, C.**, Pezeshk, S., Camp, C. V., Campbell, K. W.
119. Student: Model Selection and Epistemic Uncertainty Quantification of the Ground Motion Models for Induced Seismicity in Central East North America. **Farajpour, Z.**, Kowsari, M., Pezeshk, S.
120. Updating the USGS CEUS–WUS Attenuation Boundary—A Hazard Sensitivity Study. **Shumway, A. M.**, Petersen, M. D., Levandowski, W., McNamara, D. E., Frankel, A. D., *et al.*

The Effects of Sedimentary Basins on Earthquake Ground Motions (see page 1267).

121. Preliminary Shear-wave Velocity Site Characterization at Strong Motion Stations in Anchorage, Alaska, Using a Flexible Multimethod Approach. **Stephenson, W. J.**, Leeds, A., Ahdi, S. K., Dutta, U., Lindberg, N. S., *et al.*
122. Student: Examination of Synthetic Reno-area Basin Amplification From Small Earthquakes to 3 Hz Frequency. **Lewright, L. M.**, Louie, J. N., Assor, C. E., Graham, J. R., Prathap, A.
123. Student: Model Surface Wave Dispersion Analysis Across a Basin Boundary. **Graham, J. R.**, Louie, J. N., Assor, C. E.
124. The San Gabriel and San Bernardino Basin Project: New 3D Velocity and Structural Models in the Los Angeles Region for Improved Ground Motion Estimates. **Clayton, R. W.**, Persaud, P., Villa, V., Li, Y., Ghose, R.
125. Student: Comparative Analysis of Body- and Surface-wave Amplification in the Seattle Basin. **Jaski, E.**, Moschetti, M. P., Tsai, V. C., Bowden, D. C.
126. Student: Challenges Facing Discovery of Largest Lake in World History Geotechnical Investigation. Najafian, A., Jarahi, H., **Bayraktutan, M.**
127. Sediments Thickness Correction in GK17 Ground Motion Modeling. **Graizer, V.**
128. Sediment Thickness and Ground Motion Site Amplification Along the United States Atlantic and Gulf

Coastal Plains. **Boyd, O. S.**, Churchwell, D. H., Moschetti, M. P., Thompson, E. M., Pratt, T. L., *et al.*

129. Joint Velocity Inversion of Active-source Phase Velocity Dispersion and Ambient-vibration H/V Spectral Ratios in the Atlantic Coastal Plain Sediments, Eastern US. **Pratt, T. L.**, Parolai, S., Poggi, V., Dreossi, I.

130. Student: Paleo Mega Lake of Rey Sediments and Its Effect on Earthquake Acceleration Case Study Tehran City. **Jarahi, H.**, Moghimi, S., Tan, O., Saygılı, Ö., Karagöz, Ö.

131. Student: Revision of Iranian Seismic Design Code for Tehran Region Based on "Paleo Mega Lake of Rey" Theory. **Jarahi, H.**, Moghimi, S., Tan, O., Saygılı, Ö., Karagöz, Ö.

Thursday, 21 April 2022—Oral Sessions

Presenting author is indicated in bold.

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (see page 1325).	**Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone** (see page 1238).	**The 15 January 2022 Tonga Eruption and Tsunami** (see page 1186)	**Earthquake Source Processes at Various Scales: Theory and Observations**(see page 1252).
8:00 AM	INVITED: Seismic Source Characterization for Probabilistic and Scenario Seismic Hazard Analysis Beneath the Complex Tectonic Setting. **Miyake, H.**, Morikawa, N.	The Role of Geosciences in Informing the Seismic Risk Management of the Pacific Gas and Electric Humboldt Bay Power Plant, Humboldt County, California. Nishenko, S., Page, W. D., **Bachhuber, J.**	USGS Seismic Monitoring of the 2022 Hunga Tonga-Hunga Haʻapai Volcano Eruption. **Earle, P.**, Kintner, J., Yeck, W. L., Pursley, J., Bellini, J. J., *et al.*	The SCEC/USGS Community Stress Drop Validation Study Using the 2019 Ridgecrest Earthquake Sequence Data. **Baltay, A.**, Abercrombie, R. E., Taira, T.
8:15 AM	Catalog Harmonization Using Reliable Mws. **Gok, R.**, Onur, T., Barno, J., Walter, W. R.	Interseismic Fault Loading in California's North Coast Constrained by Geodetic Data. **Materna, K.**, Murray, J. R., Pollitz, F. F., Patton, J. R.	Seismological Characterization of Dynamic Parameters of the Hunga Tonga Explosion From Teleseismic Waves. **Poli, P.**, Shapiro, N. N. S.	Spectral Scaling Comparison and Validation Between Coda and GIT Spectra for Central Italy and Ridgecrest, CA (3.3<Mw<7.1). **Mayeda, K.**, Roman-Nieves, J. I., Bindi, D., Morasca, P., Walter, W. R., *et al.*
8:30 AM	Coda Envelope Moment Magnitudes and the Re-evaluation of Magnitude Conversion Relations for Seismic Hazard Assessment in Southeastern Canada. **Bent, A. L.**, Mayeda, K., Roman-Nieves, J. I., Shelly, D. R., Barno, J.	Characterizing Active Cross-shore Faults Along the Continental Shelf in Southern Cascadia. **Watt, J.**, Hill, J., Nieminski, N., Kluesner, J., Brothers, D. S., *et al.*	Seismic Characterization of the 2022 Hunga Tonga-Hunga Haʻapai Volcanic Eruption. **Thurin, J.**, Tape, C.	Stress Estimations of Moderate Earthquakes During the Ridgecrest Earthquake Sequence. **Ji, C.**, Assor, C. E., Bailey, B., Archuleta, R. J.
8:45 AM	A Systematic Examination of the Effects on the Seismic Hazard of Non-uniqueness in Declustering an Earthquake Catalog. **Anderson, J. G.**, Zaliapin, I.	INVITED: Plate Torture: The Gorda Deformation Zone. **Goldfinger, C.**	The Global Seismographic Network Reveals Atmospherically Coupled Normal Modes Excited by the 2022 Tonga Eruption. **Anthony, R. E.**, Ringler, A. T., Aster, R. C., Taira, T., Shiro, B., *et al.*	Characterization of Earthquake Swarms and Ruptures to Reveal Driving Mechanisms. **Abercrombie, R. E.**, Chen, X., Qin, Y.
9:00 AM	Linear Combination of GMMs Using Optimized Weights Based on Record-free Covariance. **Kwak, D.**, Ahn, J.	Sources of North Coast Seismicity Revisited: Tectonics, Moment Tensors and Finite Fault Models for the Gorda - Southern Cascadia Region. **Hellweg, M.**, Dengler, L., Lomax, A., McPhereson, R. C., Dreger, D. S.	Early Episodic Eruption Characteristics of the January 2022 Hunga Tonga-Hunga Haʻapai Volcanic Activities. **Zheng, Y.**, Hu, H., Spera, F., Scruggs, M., Mandli, K., *et al.*	Earthquake Arrest and Stress Overshoot Affect Observed Scaling of Breakdown Energy and Source-time Functions. **McLaskey, G.**, Ke, C., Kammer, D. S.

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science (see page 1204).	**The Effects of Sedimentary Basins on Earthquake Ground Motions** (see page 1263).	**Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring** (see page 1301).
8:00 AM	STUDENT: A First Look at Earthquake Early Warning in Alaska. **Fozkos, A.**, West, M. E., Gardine, M.	Blind Prediction of 3D Seismic Site Response in Near Field Extended Fault Scenarios: Application to the Nuclear Site of Cadarache, France. **Castro-Cruz, D.**, Gatti, F., Lopez-Caballero, F., Hollender, F., El Habber, E., *et al.*	INVITED: Deep-learning Seismology: Too Far, Too Close. **Mousavi, S.**
8:15 AM	Rollout of the Metro Vancouver Network-based Earthquake Early Warning System. **Zaicenco, A. G.**, Weir-Jones, I., Kassam, A.	From Trough to Basin, Regional Ground Motions and Local Amplifications in Israel—Insights From Numerical Modeling. **Tsesarsky, M.**, Glehman, J.	Post Hoc Visual Interpretation of Convolutional Neural Network Model for Earthquake Detection Using Feature Maps, Optimal Solutions and Relevance Values. Majstorovic, J., Giffard, S., **Poli, P.**
8:30 AM	Towards Public Earthquake Early Warning Across Central America. **Massin, F.**, Clinton, J. F., Boese, M., Strauch, W., Marroquín Parada, G. M., *et al.*	S-wave Site Amplification Factors of KiK-net Borehole Stations Obtained by Generalized Spectral Inversion. **Kawase, H.**, Nakano, K., Ito, E., Nagashima, F., Sun, J.	A Collaborative Research and Development Program to Advance the Use of Machine Intelligence in Nuclear Explosion Monitoring. **Reiter, D.**, Napoli, V.
8:45 AM	From Real-time Earthquake Monitoring to Earthquake Early Warning in Switzerland. **Massin, F.**, Clinton, J. F., Boese, M.	Surface Waves in Mexico City From the Pacific Coast Subduction Earthquakes. Baena-Rivera, M., Sánchez-Sesma, F. J., **Pérez-Rocha, L. E.**, Hernández-Meza, C., Cuellar-Martínez, A., *et al.*	INVITED: Machine Learning Applications and Developments at the US Geological Survey's National Earthquake Information Center for Improved Regional-to-global Scale Monitoring. **Yeck, W. L.**, Cole, H. M., Benz, H. M., Patton, J. M., Kragness, D. S., *et al.*
9:00 AM	CrowdQuake+: Noise-robust and AI-empowered Earthquake Early Warning Using Low-cost MEMS Sensors. **Kwon, Y.**, Khan, I., Lee, J., Shin, J., Ahn, J.	Seismo-VLAB: A Finite Element Simulation Platform for Basin-scale 3D Site Response Analyses. **Asimaki, D.**, Kusanovic, D. M., Ayoubi, P., Mohammadi, K.	Estimation of Hypocentral Parameters Based on Graph Neural Networks. **Matos Chuquiuri, A. O.**, Moya Huallpa, L. A., Gonzales, C., Mas, E., Koshimura, S., *et al.*

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
9:15–10:00 AM	Poster Break			
	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (see page 1325).	**Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone** (see page 1238).	**Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors** (see page 1280).	
10:00 AM	INVITED: Ground Motion Models: Which Way Henceforth? **Atkinson, G. M.**	The 1992 Cape Mendocino Earthquake: A Turning Point in US Tsunami Hazard Mitigation. **Dengler, L.**, Patton, J. R., Wilson, R. I., Hellweg, M., Nicolini, T., *et al.*	An Examination of DAS as a Possible Earthquake Early Warning Tool. **Mellors, R. J.**, Kilb, D., Ajo-Franklin, J., Imperial Valley Dark Fiber Team	
10:15 AM	Ground Motion Simulations in Azerbaijan: Application to PSHA. **Pitarka, A.**, Onur, T., Gok, R.	STUDENT: Block Models of the Southern Cascadia Forearc Based on Geodetic Data. **Nuyen, C.**, Schmidt, D.	Seismicity Monitoring Using Sub-array Processing of Large-aperture DAS Arrays. **Karrenbach, M.**, Cole, S., Yartsev, V., Hooper, R.	
10:30 AM	PSHA Consistently Overpredicts Historically Observed Shaking Data. **Salditch, L.**, Stein, S., Gallahue, M., Neeley, J., Hough, S., *et al.*	Application of High-precision, NLL-SSST-coherence Earthquake Location to Untangle the 3D Seismo-tectonics of the Mendocino Triple-junction, Northern California. Lomax, A., McPherson, R. C., **Patton, J. R.**, Hellweg, M., Dengler, L., *et al.*	Seismic Monitoring Using Dark Fiber and Distributed Acoustic Sensing (DAS) in the Imperial Valley, California. **Templeton, D.**, Morency, C., Matzel, E., Ajo-Franklin, J.	
10:45 AM	New Approach for Modeling 3D Path Effects From Cybershake Simulations in Non-ergodic Ground-motion Models. **Abrahamson, N.**, Sung, C., Lacour, M.	A Linked Sequence of Earthquakes That Initiates at the Northern San Andreas Fault. **McPherson, R. C.**, Patton, J. R., Lomax, A.	Back-projection Imaging of the 2021 Antelope Valley m6.0 Earthquake Using Distributed Acoustic Sensing. **Li, J.**, Zhan, Z., Biondi, E., Williams, E. F.	
11:00 AM	Non-ergodic PSHA Using Fully-deterministic Physics-based Models for Southern California. **Callaghan, S. A.**, Milner, K. R., Goulet, C. A., Shaw, B. E., Maechling, P. J., *et al.*	Mendocino Triple Junction: Terraces and Tectonics in the Latest and Greatest Quaternary. **Patton, J. R.**	Phase Picking on Distributed Acoustic Sensing Data Using Semi-supervised Learning. **Zhu, W.**, Biondi, E., Ross, Z. E., Zhan, Z.	
11:30 PM–12:30 AM	SSA President's Address and Awards Ceremony			
12:30–2:00 PM	Lunch Break			

Time	Cedar*	Regency A–C	Regency E–G
9:15–10:00 AM	Poster Break		
	Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science (see page 1204).	**Earthquake Source Processes at Various Scales: Theory and Observations**(see page 1252).	**Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring** (see page 1301).
10:00 AM	Seismic Station Expected Value Metrics for Earthquake Early Warning Networks. **Biasi, G.**, Stubailo, I., Alvarez, M.	STUDENT: Bayesian Dynamic Source Inversion With Rate-and-state Friction—Unified Seismic and Postseismic Rupture of the 2014 South Napa Earthquake. **Premus, J.**, Gallovic, F., Ampuero, J.	STUDENT: Marsquake Detection With Deep Learning. **Dahmen, N. L.**, Clinton, J. F., Meier, M., Stähler, S. C., Giardini, D.
10:15 AM	Development of a Companion Questionnaire for 'Did You Feel It?': Assessing Response in Earthquakes to Include Earthquake Early Warning. Goltz, J., Wald, D. J., **McBride, S. K.**, de Groot, R., Breeden, J., *et al.*	STUDENT: Constraining Kinematic Rupture Scenarios of an Mw 6.2 Earthquake in Central Italy. **Čejka, F.**, Pacor, F., Felicetta, C., Sgobba, S., Gallovič, F.	FastMapSVM: Classifying Seismograms Using the Fastmap Algorithm and Support Vector Machines. **White, M. C. A.**, Sarma, K., Li, A., Kumar, T., Nakata, N.
10:30 AM	Exploring Evidence-based Guidelines for Protective Actions and Earthquake Early Warning Systems. **McBride, S. K.**, Smith, H., Morgoch, M., Sumy, D. F., Jenkins, M. R., *et al.*	STUDENT: Stress-strain Characterization of Complex Seismicity Along California Faults. **Juárez Zúñiga, A.**, Jordan, T. H.	Assessing the Limits of Predictive Uncertainty in Seismic Event Discrimination Using Bayesian Neural Networks. **Garcia, J. A.**, Linville, L., Catanach, T. A.
10:45 AM	Real-time Performance of the PLUM Earthquake Early Warning Algorithm for the West Coast of the US. **Cochran, E. S.**, Kilb, D., Saunders, J. K., Bunn, J., O'Rourke, C. T., *et al.*	STUDENT: The Mw 5.7 Pica Earthquake: A Crustal Event in Northern Chile with Large Ground Accelerations and Stress Drop. **Herrera, C.**, Cassidy, J. F., Dosso, S. E., Dettmer, J., Rivera, E., *et al.*	STUDENT: Towards a Dynamic Multi-net Approach for Earthquake Association. **Chuang, L. Y.**, Williams, J., Barama, L., Peng, Z., Newman, A. V.
11:00 AM	Superconducting Earthquake Early-warning Device (SEED) for Detection of Prompt Gravity Signals from Earthquake Ruptures. **Paik, H.**, Collins, C. J., Metzler, Z., Shawhan, P. S., Meng, L., *et al.*	Reexamination of the Earthquake Source Spectrum and the Inferred Source Parameters. **Archuleta, R. J.**, Ji, C.	STUDENT: Measures for Evaluating Neural Phase Pickers on Continuous Waveform Data. **Park, Y.**, Beroza, G. C.
11:30 PM–12:30 AM	SSA President's Address and Awards Ceremony		
12:30–2:00 PM	Lunch Break		

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (see page 1325).		**Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science** (see page 1204).	**The 15 January 2022 Tonga Eruption and Tsunami** (see page 1186)
2:00 PM	PSHA Input Considerations in Central Asia. **Onur, T.**, Gok, R., Mackey, K., Berezina, A., Mikhailova, N., *et al.*		STUDENT: Real-time and Data-driven Ground Motion Prediction Equations for Earthquake Early Warning. **Chatterjee, A.**, Trugman, D. T.	What Produced the Giant Hunga Tonga-Hunga Ha'apai Eruption Cloud?. **Mastin, L. G.**, Van Eaton, A. R., Schneider, D. J., Kern, C., Schwaiger, H. F.
2:15 PM	'We're Gonna Need a Bigger Boat': Wrestling a Large Seismic Hazard Model for Seismic Risk Assessment in Canada. **Hobbs, T. E.**, Kolaj, M., Journeay, M., Rao, A.		STUDENT: Detecting Earthquakes in Noisy Real-time GNSS Data With Machine Learning. **Dybing, S. N.**, Melgar, D., Thomas, A. M., Mencin, D.	Seismic, Infrasound and Hydroacoustic Analysis of the 2022 Tonga Eruption. **Ichinose, G.**, Kim, K., Pasyanos, M. E., Rodd, R. L., Gok, R., *et al.*
2:30 PM	STUDENT: Probabilistic Seismic Hazard Assessment in Lebanon. **El Kadri, S.**, Beauval, C., Bard, P., Brax, M., Klinger, Y.		Applications of Nonergodic Site Response Models to ShakeAlert Case Studies in the Los Angeles Area. Lin, R., Parker, G. A., McGuire, J. J., **Baltay, A.**	Air Waves From the 2022 Tonga Explosion: Theoretical Studies and an Oversight in the Reporting of DART Sensor Data. **Okal, E. A.**
2:45 PM	Earthquake Recurrence Model for the Colombia–Ecuador Subduction Zone Constrained From Seismic and Geodetic Data, Implication for PSHA. Marinière, J., **Beauval, C.**, Nocquet, J., Chlieh, M., Yepes, H.		Ground Motion Forecasting for Large Events With HR-GNSS and Deep Learning. Lin, J., **Melgar, D.**, Thomas, A. M., Sahakian, V. J., Searcy, J.	The 15 January 2022 Hunga Tonga-Hunga Ha'api (HTHH) Explosive Eruption and the Challenges It Presented to the Pacific Tsunami Warning Center (PTWC). **Weinstein, S. A.**, Becker, N., Goosby, S., Koyanagi, K., McCreery, C., *et al.*
3:00 PM	A Strategy to Build a Unified Dataset of Moment Magnitude Estimates for Low-to-moderate Seismicity Regions Based on European-Mediterranean Data: Application to Metropolitan France. **Laurendeau, A.**, Scotti, O., Clément, C.		Exploring Two-station Alerting With Epic and Machine Learning Classifier. **Chung, A.**, Henson, I., Meier, M., Allen, R.	From a Boom and a Plume to Observation and Inundation: The US National Tsunami Warning Center's Unique Response to the Most Powerful Volcanic Tsunami Since Krakatoa. **Ohlendorf, S. J.**, Heath, B. A., Snider, D. J., Popham, C., Hale, D., *et al.*
3:15 PM–4:30 PM	Poster Break			

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors (see page 1280).	**Shakes in Lakes: Frontiers in Lacustrine Paleoseismology** (see page 1335).	**Seismo-geodetic Approaches for Seismic and Tectonic Processes** (see page 1332).
2:00 PM	Taiwan Milun Fault Drilling and All-inclusive Sensing (MiDAS) Project: Downhole Optical Fiber Through Frequent Slip Active Fault Zone. **Ma, K.**, Lin, C., Ku, C., Huang, H., von Specht, S., *et al.*	Towards a Paleoseismic Record of Intraslab Earthquakes in the Alaskan Subduction Zone. **Van Daele, M.**, Praet, N., Haeussler, P. J., Witter, R. C., De Batist, M.	INVITED: Imaging the Rupture Process and Postseismic Deformation of the 2019 Ridgecrest Earthquake Sequence with High-resolution Geodetic Data. **Wang, K.**, Bürgmann, R.
2:15 PM	High-resolution Eikonal Traveltime Tomography of the Long Valley Caldera Using Distributed Acoustic Sensing. **Biondi, E.**, Zhu, W., Williams, E. F., Li, J., Zhan, Z.	INVITED: Using Lacustrine Paleoshaking Evidence to Quantitatively Determine Earthquake Source Parameters. **Wils, K.**, Vanneste, K., Vervoort, M., Moernaut, J., De Batist, M., *et al.*	INVITED: Demonstrating the Utility of Seafloor Geodetic Instrumentation: A Case Study of the Simeonof-Sand Point-Chignik Earthquake Sequence Along the Alaska Subduction Zone. **DeSanto, J.**, Brooks, B., Crowell, B. W., Ericksen, T., Goldberg, D. E., *et al.*
2:30 PM	Subsurface Imaging of Distributed Acoustic Sensing Data Using a Dark Fiber Line in Reno, Nevada. **Mirzanejad, M.**, Seylabi, E., Tyler, S. W., Hatch, R., Saltiel, S., *et al.*	Lakes as Paleoseismic Records in a Seismically-active, Low-relief Area: An Example From the Rieti Basin, Central Italy. **Noble, P. J.**, Archer, C., Michetti, A., Sagnotti, L., Florindo, F., *et al.*	Validation of Peak Ground Velocities Recorded on Very-high-rate GNSS Against NGA-West2 Ground Motion Models. **Crowell, B. W.**, DeGrande, J., Dittmann, T., Ghent, J. N.
2:45 PM	Monitoring Ocean Surface Waves Offshore the Oregon Coast With Distributed Acoustic Sensing. **Viens, L.**, Spica, Z. J.	Sedimentological and Geochemical Characterization of Earthquake-generated Turbidites in Fault-proximal Glacial Lakes of the Teton Range, Grand Teton National Park, Wyoming. **Larsen, D. J.**, Blumm, A. R., Crump, S. E.	Expansion of Global GNSS-based Seismic Monitoring. **Melbourne, T. I.**, Szeliga, W. M., Santillan, M. V. I., Scrivner, C. W. I.
3:00 PM	STUDENT: DAS Can Record Storm-induced Seismic Signals in Urban Areas. **Shen, J.**, Zhu, T.	Lacustrine Paleoseismic Records of Cascadia Megathrust Earthquakes From Lake Ozette, Washington. **Brothers, D. S.**, Sherrod, B. L., Singleton, D. M., Hill, J., Ritchie, A., *et al.*	Impart of Three-dimensional Structure of Subduction Zone on Time-dependent Crustal Deformation Measured by HR-GNSS. **Fadugba, O. I.**, Sahakian, V. J., Melgar, D., Rodgers, A.
3:15 PM–4:30 PM	Poster Break		

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (see page 1325).		**Development, Enhancement and Validation of Seismic Velocity Models** (see page 1246).	
4:30 PM	Earthquake Probabilities Using the Long-term Fault Memory Model. Neely, J., **Salditch, L.**, Stein, S., Spencer, B.		Seismic Velocity – Depth Relations for San Francisco Bay Area Sediments and Effects on Simulated Ground Motion in the East Bay. **Hirakawa, E. T.**, Aagaard, B. T.	
4:45 PM	Comparison of Natural and Mining-induced Seismicity Hazard: A Case Study for Sudbury, Ontario. **Assatourians, K.**, Novakovic, M., Yenier, E., Atkinson, G. M.		Validation of the Southern California Earthquake Center (SCEC) Community Velocity Model (CVM) Version S4.26-M01 Using 0-5 Hz Deterministic 3D Ground Motion Simulations for the 2014 La Habra, California, Earthquake. **Olsen, K. B.**, Hu, Z., Day, S. M.	
5:00 PM	A Regionally Adaptable Ground-motion Model for Fourier Amplitude Spectra of Shallow Crustal Earthquakes in Europe. **Kotha, S.**, Bindi, D., Cotton, F.		Inverting for Velocity Profiles in California Using Low- and High-frequency Rayleigh-wave Dispersion With Horizontal-to-vertical Spectral Ratios. **Seylabi, E.**, Tehrani, H., Boyd, O. S.	
5:15 PM	STUDENT: High-pass Corner Frequency Selection for Implementation in the USGS Automated Ground Motion Processing Tool. **Ramos-Sepulveda, M. E.**, Parker, G. A., Thompson, E. M., Brandenberg, S. J., Li, M., *et al.*		A Large-scale Application of Multizonal Transdimensional Bayesian Inversion for Developing a 3D Geophysical Model in Basel, Switzerland. **Imtiaz, A.**, Panzera, F., Hallo, M., Dresmann, H., Steiner, B., *et al.*	
5:30 PM	STUDENT: Developing an Empirical Relationship Between Different Distances Metrics for Seismic Hazard Assessment. **Kayastha, M.**, Pezeshk, S., Tavakoli, B.		STUDENT: Three-dimensional Seismic Response of Maar Volcanic Structures. **Labuta, M.**, Burjánek, J., Opršal, I.	
6:00 PM–7:00 PM	*Plenary:* Joyner Lecture			
7:00 PM–8:00 PM	Joyner Reception			

Time	Cedar*	Regency A–C	Regency E–G
	The 15 January 2022 Tonga Eruption and Tsunami (see page 1186)	**Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere** (see page 1273).	**Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake** (see page 1298).
4:30 PM	Using Infrasound and Umbrella Cloud Radius to Estimate the Size of the Hunga Tonga Eruption. **McNutt, S. R.**, Thompson, G., Constantinescu, R., Connor, C. B.	INVITED: Development of Balloon-based Seismology for Venus Exploration. **Krishnamoorthy, S.**, Martire, L., Komjathy, A., Pauken, M. T., Cutts, J. A., *et al.*	Twenty Years of Intraplate Alaska Earthquakes Since the 2002 Denali Fault Earthquake. **Tape, C.**, McPherson, A., Smith, K., Chow, B.
4:45 PM	STUDENT: Water Level and Atmospheric Pressure Data From the Hunga Tonga-Hunga Haʻapai Tsunami: A Retrospective Analysis. **Santellanes, S.**, Melgar, D., Ruiz-Angulo, Á.	Analysis of Thermal Moonquakes Within the Apollo 17 Lunar Seismic Profiling Experiment. **Civilini, F.**, Weber, R. C., Husker, A.	New Look at the m7.9 2018 Offshore Kodiak Aftershock Sequence With the AACSE Ocean Bottom Broadband Deployment. **Ruppert, N.**, Matulka, P., Wiens, D. A.
5:00 PM	The 15 January 2022 Hunga Tonga-Hunga Haʻapai Eruption as Recorded by MERMAID. **Simon, J. D.**, Yu, Y., Pipatprathanporn, S.	An Update on the Seismicity of Mars as Recorded by InSight's Marsquake Service. **Clinton, J. F.**, Ceylan, S., Giardini, D., Horleston, A., Kawamura, T., *et al.*	Subduction Megathrust Coupling in the Shumagin Gap Region Inferred From the 2020-2021 Earthquake Sequence. **Herman, M. W.**, Furlong, K. P.
5:15 PM	STUDENT: Hunga Tonga-Hunga Haʻapai: Spectral Characteristics of Traveling Ionospheric Disturbances From the January 2022 Eruption and Tsunami. **Ghent, J. N.**, Crowell, B. W.	Lateral Variations of the Martian Crustal Thickness From Insight Measurements and the Observed Gravity Field. **Drilleau, M.**, Samuel, H., Garcia, R. F., Wieczorek, M. A., Rivoldini, A., *et al.*	INVITED: STUDENT: Structure and Kinematics of the Eastern Denali Fault From Drone and Crewed Airborne Lidar Surveys. **Finley, T.**, Salomon, G., Stephen, R., Nissen, E., Cassidy, J. F., *et al.*
5:30 PM	The Hunga Tonga-Hunga Haʻapai Eruption of 15 January 2022 Observed on the Multi-technology International Monitoring System Network. **Le Bras, R. J.**, Mialle, P., Bittner, P.	INVITED: Constraints on the Crustal Structure of Mars From P- and S-receiver Functions and Ambient Vibrations Autocorrelations. **Knapmeyer-Endrun, B.**, Panning, M. P., Joshi, R., Bissig, F., Khan, A., *et al.*	Queen Charlotte Plate Boundary: Insights From Earthquake Relocations and Seismic Tomography. **Oliva, S.**, Bostock, M., Schaeffer, A., Roecker, S., Nedimovic, M., *et al.*
6:00 PM–7:00 PM	*Plenary:* Joyner Lecture		
7:00 PM–8:00 PM	Joyner Reception		

Poster Sessions

Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake (see page 1299).

1. Estimating Vs30 in Anchorage, Alaska Using HVSR of Earthquakes vs. HVSR of Ambient Noise: A Comparison. **Feenstra, J. P.**, Thornley, J. D.
2. Catalog of Coseismic Displacements Across Alaska. **Freymueller, J. T.**, Xiao, Z., Rollins, C., Elliott, J., Grapenthin, R., *et al.*
3. Student: Relocating the 2021 and 1938 Chignik Alaska Aftershock Sequences with Station Corrections from AACSE Array to Improve Rupture Area Estimates. **Reid-McLaughlin, A. M.**, Abers, G. A., Barcheck, G.
4. Aftershock Regions of Aleutian-Alaska Megathrust Earthquakes, 1938-2021. **Tape, C.**, Lomax, A.
5. Student: Seismic Velocity Structure Near 2020-2021 Major Earthquakes at the Alaska Peninsula. **Wang, F.**, Wei, S., Ruppert, N., Zhang, H.
6. Student: Along-strike Variation in Plate-bending Seismicity and Relationship to the Seismic Cycle in the Alaska Subduction Zone. **Matulka, P.**, Wiens, D. A., Li, Z., Barcheck, G., Abers, G. A., *et al.*
7. Student: Potential Megathrust Co-seismic Slip During the Sand Point, Alaska Strike-slip Earthquake. **Santellanes, S.**, Melgar, D., Crowell, B. W., Lin, J.
8. The 2020 M7.6 Sand Point Alaska Earthquake: Slip Model, Stress Change Contributions and Tsunami Implications. Grapenthin, R., Elliott, J., Xiao, Z., **Parameswaran, R. M.**, Freymueller, J. T., *et al.*
9. Earthquakes, Interseismic Coupling and Stress Triggering Along the Eastern Alaska Subduction Margin. **Elliott, J.**, Grapenthin, R., Parameswaran, R. M., Xiao, Z., Freymueller, J. T., *et al.*

Seismo-geodetic Approaches for Seismic and Tectonic Processes (see page 1334).

10. Student: Generation and Validation of Synthetic HR-GNSS Data for New Zealand Megathrust Rupture Scenarios. **Solares-Colón, M. M.**, Melgar, D., Crowell, B. W., Howell, A., D'Anastasio, E., *et al.*
11. Reconciling Seismic and Geodetic Magnitude Estimates for Rapid Earthquake Characterization. **Parameswaran, R. M.**, Grapenthin, R., West, M. E., Fozkos, A.
12. Student: Earthquake Detection Sensitivity of GPS Time-differenced Carrier Phase Velocities. **Dittmann, T.**, Hodgkinson, K., Morton, J., Mencin, D., Mattioli, G.
13. Spatiotemporal Variations of Stress and Strain in the Crust Near 2019 Ridgecrest Earthquake Sequence. **Abolfathian, N.**, Fielding, E. J.
14. Tectonic Tremor Used as a Proxy for Slow Slip Can Be Used to Remove Its Effect From a GNSS Signal and Reveal Changes Due to Annual Rainfall. **Husker, A.**, Santoyo, M., Alvarado-Santiago, G., Radiguet, M., Kazachkina, E., *et al.*
15. Student: Multifractal Analysis of Point Source Distributions Obtained From InSAR Inversion. **Saylor, C.**, Rundle, J. B.

Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone (see page 1241).

16. The December 2021 Cape Mendocino Earthquake Sequence. **Hellweg, M.**, Dreger, D. S.
17. Revisiting the M6.5 21 December 1954 Korbel Earthquake. **Hellweg, M.**, McPherson, R. C., Dengler, L., Dreger, D. S.
18. The Humboldt Bay Seismic Network: 1974 to 1986. McPherson, R. C., **Dengler, L.**
19. The Redwood Coast Tsunami Work Group: Twenty-five Years of Evolving Outreach on California's North Coast. **Dengler, L.**, Admire, A., Ozaki, V., Nicolini, T., Aylward, R.
20. The Seismic Saga of the Humboldt Bay Nuclear Power Plant. **Dengler, L.**, McPherson, R. C.
21. Tsunami Hazard Mapping: Comparison of California Mapping with Oregon Mapping. **Patton, J. R.**, Wilson, R. I., Allan, J.

Shakes in Lakes: Frontiers in Lacustrine Paleoseismology (see page 1336).

22. Hunting For Norway's Biggest Historical Earthquake. **Redfield, T. F.**, Lakeman, T., Hermanns, R. L., Fabian, K., Klugh, M.
23. Are Wasatch Front Earthquakes Preserved in the Great Salt Lake Sedimentary Record? **DuRoss, C. B.**, Brothers, D. S., Thompson Jobe, J. A., Briggs, R. W., Singleton, D. M., *et al.*
24. Student: Investigating Earthquake Rupture History of the Cascadia Subduction Zone Using Coastal Lacustrine Diatoms, Lake Ozette, Washington, USA. **DePaolis, J. M.**, Dura, T., Brothers, D. S., Singleton, D. M., Sherrod, B. L.
25. Developing a Chronology of Crustal and Megathrust Earthquake Records in the Pacific Northwest: Preliminary Results from Lakes Whatcom and Sammamish in Washington. **Hill, J.**, Brothers, D. S., Sherrod, B. L., Dartnell, P., Ponton, C., *et al.*
26. Constraining the Initiation, Spatial Distribution and Sedimentary Source of Lake Turbidites Triggered by the 2018 Anchorage Earthquake. **Singleton, D. M.**, Brothers, D. S., Haeussler, P. J., Witter, R. C., Hill, J.
27. Preliminary Lacustrine Paleoseismology From Chelatna Lake, Southcentral Alaska, From Chirp Profiles and Short

Cores. **Haeussler, P. J.**, Singleton, D. M., Witter, R. C., Brothers, D. S., Hill, J.

Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere (see page 1274).

28. Detection of Seismic Events Originating from Europa's Silicate Interior. **Marusiak, A. G.**, Panning, M. P., Vance, S., Nunn, C., Stähler, S. C., *et al.*
29. Student: Classifying Deep Moonquakes Using Machine Learning Algorithms. **Khatib, A. S.**, Schmerr, N. C., Lekic, V., Maguire, R.
30. Investigating the Heterogeneous Nature of the Deep Martian Mantle With Geodynamically-constrained Inversions of InSight Seismic Data. **Samuel, H.**, Drilleau, M., Garcia, R. F., Rivoldini, A., Lognonne, P., *et al.*
31. Student: Deep and Shallow Quakes in the Presence of a Clathrate-lid on Titan. **Bryant, A. S.**, Panning, M. P., Marusiak, A. G.
32. Mars Interior Revealed From Over Three Years of InSight on Mars. **Panning, M. P.**, Banerdt, W. B., Smrekar, S. E.
33. Constructing an Earthquake Site Response Model for the Lunar South Polar Region. **Schleicher, L. S.**, Schmerr, N. C., Watters, T. R., Banks, M. E., Bensi, M. T., *et al.*
34. Lunar Gravitational-wave Antenna. Harms, J., Bonforte, A., Frigeri, A., Giunchi, C., van Heijningen, J., Komatsu, G., Majstorović, J., Marka, S., Melini, D., Olivieri, M., **DeSalvo, R.**, The LGWA Collaboration

Everything Old Is New Again—Resurging Use of Analog Data (see page 1263).

41. A Directory for the Discovery of Legacy Seismic Data. **Hwang, L. J.**, Kwong, D.
42. The ISC Electronic Archive of Printed Station and Network Bulletins. Di Giacomo, D., Armstrong, A., **Storchak, D. A.**
43. WFNE Repository and Nuclear Explosion Legacy Data. Oancea, V., Murphy, J. R., **Kung, Y.**, Piraino, P. E.
44. Nuclear Explosion Legacy Data in Central and Eastern Europe. Oancea, V., **Kung, Y.**, Murphy, J. R., Piraino, P. E., Popa, M., *et al.*
45. Recovery and Digitization of Soviet Peaceful Nuclear Explosions From Legacy Analog Seismograms. **Mackey, K.**, Alexei, M., Vinogradov, Y., Dyagilev, R., Butyrin, P., *et al.*
46. Student: Revisiting the M7.3 1948 Ashgabat Earthquake Using Historic Seismograms and Satellite Imagery. Marshall, N., **Ou, Q.**, Walker, R., Grützner, C., Bergman, E.
47. Student: Examining Digitization Parameters to Produce High Quality Data from Historical Analog Seismograms. **Stibitz (Burkhard), K.**, Burk, D., Mackey, K.

Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science (see page 1207).

48. Student: MyShake + ShakeAlert: Using Smartphone Seismic Data for Earthquake Early Warning. **Patel, S. C.**, Chung, A., Strauss, J., Allen, R., Kong, Q.
49. Earthquake Location Performance of ShakeAlert's Epic Algorithm for Recent Offshore Events Near Cape Mendocino, California. **Williamson, A.**, Chung, A., Allen, R.
50. Can PLUM Earthquake Early Warning (EEW) Ground Motion Estimates in Southern California Be Improved by Incorporating Empirically Derived Site-Term Corrections? Kilb, D., Bunn, J., Devin, E., Parker, G. A., Baltay, A., Saunders, J. K., **Cochran, E. S.**, Minson, S. E., Clements, T., O'Rourke, C. T.
51. The Potential for Small-world Phenomena in Ground Motion-based Earthquake Early Warning. **Clements, T.**, Cochran, E. S., Yoon, C., Minson, S. E., Baltay, A.
52. Enabling Inclusion of Magnitude Estimates Based on Peak Ground Displacement in the ShakeAlert Solution Aggregator. **Murray, J. R.**, Crowell, B. W., Ulberg, C., Hagerty, M., Smith, D. E., *et al.*
53. Testing the Finite-fault Rupture Detector (FinDer) in New Zealand. Böse, M., Behr, Y., **Massin, F.**, Andrews, J.
54. An Earthquake Early Warning System for the Lower Rhine Embayment, Germany. Najdahmadi, B., **Pilz, M.**, Razafindrakoto, H., Oth, A., Cotton, F.
55. Low-latency Digitization, Communication and Alerting for Earthquake Early Warning Systems: Güralp Minimus. **Lindsey, J. C.**, Reis, W., Watkiss, N., Hill, P., Cilia, M.
56. Student: Qube Network: A Low-cost Consumer Seismic Network for Earthquake Monitoring and Earthquake Early Warning. **He, V.**, Clayton, R. W.
57. Performance and Effectiveness of Earthquake Early Warning in Mitigating Seismic Risk. Böse, M., Papadopoulos, A. N., Danciu, L., **Clinton, J. F.**, Wiemer, S.
58. How Low Should We Alert? Quantifying Intensity Threshold Alerting Strategies for Earthquake Early Warning in the United States. **Saunders, J. K.**, Minson, S. E., Baltay, A.
59. Testing the Latency and Geofence of Wireless Emergency Alerts Intended for the ShakeAlert® Earthquake Early Earning System, West Coast, USA. **McBride, S. K.**, Sumy, D. F., Llenos, A., Parker, G. A., McGuire, J. J., *et al.*
60. ShakeAlert Past Present and Future: Analysis of ShakeAlert's Time-to-alert Using the BDSN. **Terra, F.**, Valen, C., Boyd, O., Marty, J., Henson, I., *et al.*

Development, Enhancement and Validation of Seismic Velocity Models (see page 1248).

61. Deep Crustal P and S Wave Velocity Models for Oklahoma Based on Common-mid-point Sorting and Stacking of Local Earthquake Waveforms. **Ratre, P.**, Carpenter, B. M., Behm, M.
62. 3D Wave Propagation Simulations of m6.5+ Earthquakes on the Tacoma Fault Considering the Effects of Topography, a Geotechnical Layer and a Near-fault Damage Zone. **Stone, I.**, Wirth, E. A.
63. Student: Mapping Los Angeles Basin Depth With Converted Seismic Phases. **Yang, Y.**, Clayton, R. W.
64. Incorporating Realistic Near-surface Structure Into the Cascadia Seismic Velocity Model for 3D Earthquake Simulations. **Wirth, E. A.**, Grant, A., Stone, I., Frankel, A. D., Stephenson, W. J.
65. Student: High Resolution 3D Shear Wave Velocity Model of Salt Lake Valley via Joint Inversion of Rayleigh Wave Ellipticity and Phase Velocity From the Magna Aftershock Nodal Array. **Zeng, Q.**, Lin, F., Allam, A. A.
66. Student: A High-resolution Phase Velocity Inversion for Crustal Structure of the Southeastern US Using Non-linear Signal Comparison. **Barman, D.**, Pulliam, J. R.
67. Student: Calibration, Validation and Application of a Seismic Velocity Model for Coastal South America Using 3D Deterministic Numerical Simulations. **Xu, K.**, Roten, D., Olsen, K. B.
68. 3D P- and S-wave Active-Source Seismic Tomography of Rock Valley, the Nevada National Security Site. **Harding, J. L.**, Preston, L. A., Bodmer, M. A.

Fault Damage Zones: What We Know and Do Not (see page 1278).

69. Long-distance Propagation of Guided Waves Along Ridgecrest Faults and Evaluation of Connectivity With the Owens Valley and Garlock Faults. **Catchings, R. D.**, Goldman, M. R., Chan, J. H., Steidl, J. H., Criley, C. J.
70. High-resolution P-wave Velocities Across the Creeping Section of the San Andreas Fault at Mee Ranch, Central California. **Goldman, M. R.**, Catchings, R. D., Nevitt, J. M., Chan, J. H., Sickler, R. R., *et al.*
71. Student: Internal Variations of the Banning and Mission Creek Fault Zones Near the Thousand Palms Oasis Preserve From a Large-N Seismic Array. **Reinhard, H. R.**, Share, P.
72. Student: Characterization of Damage Zone Structure Along the Elsinore and Superstition Hills Faults: Towards Quantification of Mmax. **Gaston, H. E.**, Griffith, A., Rockwell, T. K.
73. Student: Margin-scale Damage Zone Along the Queen Charlotte Fault. **Perrin, R.**, Lauer, R., Miller, N., Brothers, D. S.
74. Student: Structure and Geometry of an Exposed Active Subduction Zone Splay Fault: The Deception Creek Strand of the Patton Bay Fault, Montague Island, Alaska. **Fintel, A.**, Tobin, H., Haeussler, P. J., Witter, R. C., O'Sullivan, P.
75. Seismic Imaging Across the San Gregorio Fault Zone at Pescadero, California. **Chan, J. H.**, Catchings, R. D., Goldman, M. R., Rymer, M. J., Criley, C. J., *et al.*
76. Mid-crustal Structure of an Exhumed, Multiply Reactivated Proterozoic Plate Boundary: Active-source and Borehole Seismic, Geologic Mapping and 3D Microgravity in the Homestake Shear Zone, Colorado. **Levandowski, W.**

Earthquake Source Processes at Various Scales: Theory and Observations (see page 1256).

77. Analysis of the 2015 Gorkha-Dolakha (Central Nepal) Foreshocks and Aftershocks Sequence Through Transients in B Values. **Parija, M.**
78. Student: Lab-generated Earthquakes in Heterogeneous Faults With Varying Roughness. **Brotherson, L.**, Edwards, B., Faulkner, D.
79. Student: Seismic Magnitude Clustering Is Prevalent in Laboratory and Field Catalogs. **Gossett, D.**, Brudzinski, M. R., Xiong, Q., Lin, Q., Hampton, J. C.
80. Student: Velocity Structure and Deep Earthquakes Beneath the Kinnaur, NW Himalaya: Constraints From Relocated Seismicity and Moment Tensor Analysis. **Biswal, S.**, Kumar, S.
81. Student: Scattering of Moment Tensors During Aftershock Sequences at Global and Local Scales. **Wilding, J.**, Ross, Z. E.
82. Toward a Self-consistent Mw Catalog for the Central Walker Lane Fault System. **Taira, T.**, Mayeda, K., Roman-Nieves, J. I., Gok, R., Walter, W. R., *et al.*
83. Fault Interactions Enhance High-frequency Earthquake Radiation. **Chu, S.**, Tsai, V. C., Trugman, D. T., Hirth, G., Elbanna, A.
84. A New Focal Mechanism Calculation Algorithm Using Inter-event Relative Radiation Patterns. **Cheng, Y.**, Allen, R.
85. A Fast Procedure to Estimate the Prevailing Rupture Propagation Direction and How It Applies to the 2016-2017 Central Italy Seismic Sequence. **Calderoni, G.**, Di Giovambattista, R., Ventura, G.
86. Student: Effects of Station Distribution and Rupture Directivity on Stress Drop Estimates in the Ridgecrest 2019 Earthquake Sequence. **Neupane, A. S.**, Ruhl, C. J., Abercrombie, R. E.

87. Characterization of Foreshocks for Mainshocks (Mj3.0 to 7.2) of Onshore Japan During 2001 to 2021. **Peng, H.**
88. Student: Insights on Earthquake Source Processes From the 2019 Ridgecrest Earthquake Source Spectra and Its Azimuthal Variation. **Liu, M.**, Neo, J., Huang, Y.
89. The Southern Alps Long Skinny Array (SALSA): Virtual Earthquake Analysis of the Alpine Fault Between Milford Sound and Maruia. **Townend, J.**, Holden, C., Chamberlain, C. J., Warren-Smith, E., Juarez-Garfias, I., *et al.*
90. Relocation of the 1975 Oroville ML 5.7 Earthquake Sequence and Insights Into Its Origin. **Smith, S.**, Wong, I. G., Humphrey, J., Hoirup, D.
91. Student: Mainshock-aftershocks and Swarm Sequences Highlighted by Fluid-driven Process (Ubaye Region, French Western Alps). **Baques, M.**, De Barros, L., Godano, M., Duverger, C., Jomard, H.

Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring (see page 1303).

92. Student: Using Machine Learning to Improve Pacific Northwest Earthquake Catalog. **Ni, Y.**, Denolle, M. A.
93. Student: Automated Real-time Earthquake Energy Discriminator of Deep Earthquakes: A Comparison of Conventional and Ml Methods. **Barama, L.**, Newman, A. V.
94. Expansion and Transferability of Seismic Deep CNN Denoiser to Global Networks. **Koch, C.**, Tibi, R., Young, C. J.
95. Deep Learning Seismic Signal Detection on the International Monitoring System. Heck, S. L., **Garcia, J. A.**, Young, C. J.
96. Analysis of the 2020 Albanian Durres Aftershock Sequence, Benchmarking Machine Learning Approaches. **Rietbrock, A.**, Woollam, J., Van der Heiden, V., Dushi, E., Schurr, B., *et al.*

Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors (see page 1282).

97. High-resolution Ambient Seismic Noise Monitoring of Geothermal Systems in California's Imperial Valley Using Dark Fiber Distributed Acoustic Sensing (DAS). **Rodríguez Tribaldos, V.**, Cheng, F., Nayak, A., Wood, T., Robertson, M., *et al.*
98. Reno, Nevada Dark Fiber DAS Experiment: Frequency Response Among Various Seismic Instruments. **Hatch-Ibarra, R. L.**, Seylabi, E., Mirzanejad, M., Tyler, S. W., Saltiel, S., *et al.*
99. Student: Directional Sensitivity of DAS and Its Effect on Rayleigh Wave Tomography. **Fang, J.**, Yang, Y., Shen, Z., Biondi, E., Wang, X., *et al.*
100. Student: De-noising DAS Data Using an Adaptive Frequency-wavenumber Filter. **Isken, M. P.**, Heimann, S., Dahm, T.
101. Student: Towards Inversion of the Microseismic Moment Tensor With DAS: Application to Boreholes. **Tuinstra, K. B.**, Lanza, F., Fichtner, A., Zunino, A., Grigoli, F., *et al.*
102. A Comparison of Approaches To Convert DAS Measurements to Ground Motion. **St. Clair, J. T.**, Sprinkle, P., Chojnicki, K., Knox, H.
103. Combining Dark Fiber and Seismic Interferometry to Measure Physical Properties of an Earthquake Swarm. **Matzel, E.**, Morency, C., Templeton, D., Ajo-Franklin, J.
104. Local Earthquake Detectability Using Long-haul Fiber Cables With DAS Technology. **Chen, X.**, McKnight, J. G., Hu, Y., Hu, M., Li, Z., *et al.*
105. Initial Steps Towards a DAS Metadata Model. **Mellors, R. J.**, Hodgkinson, K., DAS RCN Data Management Working Group

Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal? (see page 1330).

106. Composite ShakeMaps for Earthquake Sequences and for Testing and Observed Probabilistic Seismic Hazard Analyses. **Quitoriano, V.**, Salditch, L., Powers, P. M., Wald, D. J.
107. Evaluating Ground Motions From Deep Earthquakes in Malawi. **Holmgren, J. M.**, Werner, M. J., Goda, K., Silva, V., Villani, M.
108. Homogeneization of the Moment Magnitude Estimates Available in the French Datasets and Implications on Ground Motion Model Variability. **Laurendeau, A.**, Kotha, S.
109. A First Look at the Revised Seismic Hazard in Southwest Iceland From Synthetic Finite-fault Earthquake Catalogs Predicted by a New Physics-based Bookshelf Fault System Model. **Kowsari, M.**
110. Student: Precariously Balanced Rock Validation of Earthquake Ground-motion Models in Southern California. **Rood, A. H.**, Rood, D. H., Balco, G., Stafford, P. J., Brune, R. J., *et al.*

The 15 January 2022 Tonga Eruption and Tsunami (see page 1189).

111. Tonga Tsunami Modeling. **Titov, V. V.**, Wei, Y., Moore, C., Sannikova, N., Arcas, D.
112. World-wide Simulation of Ocean-coupled Air Waves Generated by the 2022 Volcanic Explosion in Tonga. **Okal, E. A.**, Salaree, A.

113. Array Studies of the Propagation of Air Waves From the Tonga Explosion at Two European Arrays. **Okal, E. A.**, Dias, F., Bergin, C., Kokina, T., Kalligeris, N., *et al.*
114. An Antipodal Seismic and (Infra)acoustic View on the 15 January 2022 Hunga-Tonga Hunga-Haʻapai Eruption from Central Europe. Kraft, T., **Ling, A.**, Toledo, T., Stähler, S., Clinton, J., *et al.*
115. The 15 January 2022 Event at Hunga Tonga-Hunga Haʻapai, Recorded by Multiparametric Stations in Italy. Braun, T., Bonforte, A., Cannata, A., Catania, R., Cesaroni, C., Delle Donne, D., Ippolito, A., Di Lieto, B., Lorenzetti, A., Massa, M., Maugeri, R., Peluso, R., Privitera, E., Rizzo, A., Romano, P., Sciotto, M., Spogli, L., **Hellweg, M.**, Doglioni, C.
116. Effects and Observations in Canada of the 15 January 2022 Hunga Tonga-Hunga Haʻapai Eruption. **Bent, A. L.**, McCormack, D. A.
117. Observations of the 15 January 2022 Tsunami in Tidal Lagoons of S.E. Australia. Moresi, L., **Miller, M. S.**
118. California Geological Survey Tsunami Event Response Program: Tonga Tsunami 2022. **Patton, J. R.**, Wilson, R. I., Bott, J., Graehl, N. A., Pridmore, C., *et al.*
119. Improving Tsunami Event Response and Decision Support Tools in California Based on an Assessment of the Tsunami Generated by the 15 January 2022 Hunga Tonga-Hunga Haʻapai Volcano Eruption. **Wilson, R. I.**, Patton, J. R., Bott, J., Graehl, N. A., Olson, B. P. E., *et al.*
120. Tsunami Response and Observations in Santa Cruz, California, USA From the 15 January 2022 Hunga Tonga-Hunga Haʻapai Volcano Eruption. **Graehl, N. A.**, Bott, J., Patton, J. R., Wilson, R. I., La Selle, S., *et al.*
121. The 15 January 2022 Tonga Tsunami Advisory on California's North Coast: Notification, Response and Outreach. **Dengler, L.**, Admire, A., Nicolini, T., Aylward, R., LaDuke, Y.
122. Tsunami Velocity and Water Height Measurements of the 2022 Tonga Event Along Northern California and Southern Oregon. Crawford, G., Admire, A., **Dengler, L.**
123. Hunga-Tonga Games: Unravelling the Timing and Size of the Biggest Volcanic Explosion in 30 Years. **Thompson, G.**, McNutt, S. R., Scruggs, M., Spera, F., Zheng, Y., *et al.*
124. Source Characterization of the 15 January 2022 Hunga Tonga-Hunga Haʻapai Eruption Using Regional and Teleseismic Waveform Analysis. **Garza-Giron, R.**, Lay, T., Pollitz, F., Kanamori, H., Rivera, L.
125. Seismoacoustic Yield Estimation of the January 2022 Hunga-Tonga Eruption. **Delbridge, B. G.**, Alfaro-Diaz, R., Begnaud, M. L., Blom, P., Carmichael, J. D., *et al.*

Friday, 22 April 2022—Oral Sessions

Presenting author is indicated in bold.

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Earthquakes in the Urban Environment (see page 1260).	**New Developments in Physics- and Statistics-based Earthquake Forecasting** (see page 1317).	**Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions** (see page 1285).	**Earthquake Source Processes at Various Scales: Theory and Observations** (see page 1341).
8:00 AM	Assessment of Earthquake Hazard and Risk for Tofino, British Columbia. Novakovic, M., Borozan, J., Yenier, E., **Assatourians, K.**, Atkinson, G. M., *et al.*	Space-time Variations of Seismicity: Quantitative Assessment and Systematic Changes Before Large Earthquakes. **Zaliapin, I.**, Ben-Zion, Y.	Influence of Subducting Rift Propagator Wakes on Cascadia Forearc Deformation and Earthquake Segmentation. **Goldfinger, C.**, Beeson, J.	STUDENT: Are Most Earthquakes' Non-double-couple Components Artifacts? **Rösler, B.**, Stein, S.
8:15 AM	Recorded Earthquake Response of the New Self Anchored Suspension (SAS) Bridge of the San Francisco Bay Bridge System–A Preliminary Study. **Celebi, M.**	STUDENT: A b-value Based Analysis of Earthquake Sequences for Japan Using Deep Learning. **Köhler, J.**, Li, W., Chakraborty, M., Faber, J., Fenner, D., *et al.*	INVITED: Upper Plate Structure and Tsunamigenic Faults Near the Kodiak Islands, Alaska. **Ramos, M. D.**, Liberty, L. M., Haeussler, P. J.	S/P Amplitude Ratios Derived from Single-component Seismograms and Their Potential Use in Resolving Focal Mechanism Complexity of Micro-earthquake Sequences. **Shelly, D. R.**, Skoumal, R. J., Hardebeck, J. L.
8:30 AM	Ground Motion Spatial Variability Due to Combined Effects of Site and City Responses in a Sedimentary Basin. Rohmer, O., **Bertrand, E.**, Régnier, J., Glinsky, N., Santisi D'Avila, M.	Physical Properties of the Crust Influence Aftershock Locations. **Hardebeck, J. L.**	Evaluating Rupture Models of the 1700 CE Tsunami With Detailed Mapping of Tsunami Deposits and Sediment Transport Modeling. **La Selle, S.**, Nelson, A., Jaffe, B., Witter, R. C., Gelfenbaum, G., *et al.*	Utility of Seismic Source Mechanisms in Mining. **Malovichko, D.**
8:45 AM	STUDENT: Testing Machine Learning Models for Regional Scale Building Damage Prediction. **Ghimire, S.**, Guéguen, P., Giffard-Roisin, S., Schorlemmer, D.	STUDENT: Does Abundant Afterslip Mean Productive Aftershock Sequences? **Churchill, R. M.**, Werner, M. J., Biggs, J., Fagereng, A.	INVITED: STUDENT: The 2021 South Sandwich Island Mw 8.2 Earthquake: A Slow Event Sandwiched Between Regular Ruptures. **Jia, Z.**, Zhan, Z., Kanamori, H.	Because Small Earthquakes Matter: Lessens Learned From Extensive Testing of CMT Inversion for Regional Earthquakes. **Petersen, G.**, Cesca, S., Heimann, S., Niemz, P., Dahm, T., *et al.*
9:00 AM	INVITED: STUDENT: High-resolution Amplification Model for an Urban Area Using the Weak Motion From Earthquakes and Ambient Vibration Data. **Janusz, P.**, Perron, V., Knellwolf, C., Bonilla, L., Fäh, D.	INVITED: Finding the Next Layer of Seismicity Patterns in High-resolution Catalogs. **Page, M. T.**, van der Elst, N.	3D Acoustic-elastic Coupling with Gravity: The Dynamics of the 2018 Palu, Sulawesi Earthquake and Tsunami. Krenz, L., Uphoff, C., Ulrich, T., **Gabriel, A.**, Abrahams, L. S., *et al.*	Detection Limits and Near-field Ground Motions of Fast and Slow Earthquakes. **Kwiatek, G.**, Ben-Zion, Y.

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	Advances in Seismoacoustic Methods for Explosion Monitoring (see page 1223).	**Distributed Deformation from Surface Fault Rupture** (see page 1249).	**Site Response Characterization in Seismic Hazard Analysis** (see page 1338).
8:00 AM	Aftershocks of the Announced Underground Nuclear Tests Conducted by the DPRK Found by Waveform Cross Correlation: From 2013 to 2022. Kitov, I., **Le Bras, R. J.**, Wang, H.	Distributed Deformations for Dip Slip Events Within PFDHA. **Moss, R.**, Thompson, S. C., Kuo, C., Younesi, K., Chao, S.	STUDENT: Evaluation of the P-wave Seismogram Approach to Estimate Vs30 in California. **Li, M.**, Rathje, E. M.
8:15 AM	ML:MC Applied to Nuclear Explosions Detonated at the Nevada Test Site. **Holt, M. M.**, Koper, K. D., Pyle, M., Walter, W. R.	Distributed Fault Displacement Hazard Assessment at a Critical Facility in Southern California: Lessons Learned From Comparing Site Data to Empirical Models for Probabilistic Hazard Analysis. **Thompson, S. C.**, Zandieh, A., Lindvall, S. C., Hartleb, R., Rockwell, T. K.	STUDENT: Estimation of Vs30 using the P-wave Seismogram Method in California, USA. **Mun, E.**, Kim, B.
8:30 AM	Moment Tensors and Explosion Monitoring. **Pasyanos, M.**, Chiang, A., Ichinose, G., Ford, S. R., Walter, W. R.	Asymmetrical Surface Rupture Width and Dependence on Shallow Fault Geometry and Topographic Slope in a >100-Year-Old Reverse Faulting Rupture, Kyrgyzstan. **Elliott, A. J.**, Wilkinson, R., Arrowsmith, R., Dianala, J. D., Tsai, C., *et al.*	Evaluation of the Vs30-Kappa Relationship for Anchorage, Alaska. **Thornley, J. D.**, Dutta, U., Douglas, J., Yang, Z.
8:45 AM	3D Nonlinear Modeling of Underground Nuclear Explosions and the Generation of Seismic Waves. **Stevens, J.**, O'Brien, M. S.	Role of Fault Maturity on the Relationship Between Surface Displacement and Rupture Length. Wang, Y., **Goulet, C. A.**	Estimating Shallow Shear-wave Velocity Profiles in Alaska Using the Initial Portion of P-waves From Local Earthquakes. **Skarlatoudis, A.**, Thio, H., Somerville, P. G.
9:00 AM	Stochastic Methods for Full Moment Tensor Inversion and Uncertainty Quantification. **Thurin, J.**, Ding, L., Liu, Q., Modrak, R., Gupta, A., *et al.*	STUDENT: Quantifying Near-field Ground Displacements in Historical Normal Earthquakes Using Optical Image Correlation. **Andreuttiova, L.**, Hollingsworth, J., Vermeesch, P., Mitchell, T.	Three-dimensional S-wave Velocity Model of Napa, California Obtained from Microtremor Array Measurements and Horizontal to Vertical Spectral Ratio. **Hayashi, K.**, Burns, S., Roughley, C.

Time	Grand A	Grand B	Grand C	Grand E–K*
9:15–10:00 AM	Poster Break			
	Earthquakes in the Urban Environment (see page 1260).	**New Developments in Physics- and Statistics-based Earthquake Forecasting** (see page 1317).	**Structure and Seismogenesis of Subducting Slabs** (see page 1345).	
10:00 AM	Urban Seismology: Installing a BASIN Seismic Array in Yangon, Myanmar During COVID-19. **Persaud, P.**, Thant, M., Kyaw, Z., Win, K., Oo, T., *et al.*	STUDENT: How Can Probabilistic Forecasts Learn From Physics-based Simulators? A Full-bayesian Approach to Forecast Recalibration. **Vazquez, L.**, Jordan, T. H.	INVITED: Deep Slab Seismicity Limited by Rate of Slab Deformation in the Transition Zone. **Billen, M.**, Fildes, R. A., Thielmann, M.	
10:15 AM	INVITED: STUDENT: Continuous Seismic Monitoring of a Building Over 20 Years. **Williams, E. F.**, Heaton, T. H., Zhan, Z., Lambert, V.	STUDENT: Statistical Analysis of Low-frequency Earthquake Catalogs. **Ducellier, A.**	Deep Earthquake Stress Drops and Body-wave Tomography of the Tonga Subduction Zone. **Wei, S.**, Tian, D., Wang, F., Adams, A., Wiens, D. A.	
10:30 AM	STUDENT: A New Approach for Soil-structure Interaction Assessment and Its Application to the Matera Experiment. **Skłodowska, A.**, Parolai, S., Petrovic, B., Romanelli, F.	STUDENT: Relaxing ETAS's Assumptions to Better Capture the Real Behavior of Seismicity. **Mizrahi, L.**, Nandan, S., Savran, W. H., Wiemer, S., Ben-Zion, Y.	STUDENT: Aftershock Properties of Intermediate-depth Earthquakes Beneath Japan: Implications for Rupture Mechanism. **Baez, C. M.**, Warren, L.	
10:45 AM	STUDENT: Numerical Coupling Of 3D Physics-based Ground Motion Simulation With Structural Response. **Sangaraju, S.**, Paolucci, R., Smerzini, C.	STUDENT: The Neural Temporal Point Process: A Scalable and Flexible Tool for Earthquake Forecasting. **Dascher-Cousineau, K.**, Shchur, O., Brodsky, E. E., Günnemann, S.	STUDENT: Aftershock Distributions, Moment Tensors and Stress Evolution of the 2016 Iniskin and 2018 Anchorage Mw 7.1 Alaskan Intraslab Earthquakes. **Drolet, D.**, Bostock, M., Plourde, A., Sammis, C. G.	
11:00 AM	STUDENT: Seismic Soil-structure Interaction Analysis of Multi-story RC Building Subjected to Different Earthquake Ground Motions Considering Various Soil Types. **Faizan, A.**, Kirtel, O.	Neural-network Based Models for Earthquake Rate Prediction. Zlydenko, O., **Bar-Sinai, Y.**, Elidan, G., Hassidim, A., Kukliansky, D., *et al.*	Duplex and Moho Earthquakes Beneath the Lesser Himalaya in India. **Mendoza, M. M.**, Ghosh, A., Rai, S. S.	
11:30 AM–12:30 PM	*Plenary:* Frontiers in Seismology			
12:30–2:00 PM	Lunch Break			

Time	*Cedar**	*Regency A–C*	*Regency E–G*
9:15–10:00 AM	Poster Break		
	Advances in Seismoacoustic Methods for Explosion Monitoring (see page 1223).	**Earthquake Source Processes at Various Scales: Theory and Observations** (see page 1341).	**Site Response Characterization in Seismic Hazard Analysis** (see page 1338).
	Developing a Consistent Travel-time Framework for Comparing Three-dimensional Velocity Models for Seismic Location Accuracy. **Begnaud, M.**, Davenport, K., Conley, A., Ballard, S., Hipp, J.	Source Spectral Properties of Earthquakes in the Yellowstone Caldera. **Florez, M. A.**, Strozewski, B., Ross, Z. E.	What Are the Primary Site Response Parameters and Proxies? **Wang, Z.**, Carpenter, S.
10:15 AM	3D SEM Modeling of Wave Propagation at the Source Physics Experiment Phase II Site to Quantify Shear Wave Generation by Explosions at Short Distance (<3km). **Larmat, C.**, Chen, T., Abrams, J., May, A. P., Alfaro-Diaz, R. A., *et al.*	Investigation of the Induced Earthquake Sequence Near Stanton, Texas. **Woo, J.**, Ellsworth, W. L.	How Well Can We Predict Earthquake Site Response So Far? Machine Learning vs. Physics-based Modeling. **Zhu, C.**, Cotton, F., Kawase, H., Nakano, K.
10:30 AM	Acoustic Arrivals From Weak Explosive Sources Recorded on Distant Airborne Platforms. **Bowman, D. C.**, Krishnamoorthy, S., Silber, E. A.	Stress and Fluid Earthquake Triggering During the 2015–2017 Pamir Earthquake Sequence. **Bloch, W.**, Schurr, B., Ratschbacher, L., Metzger, S., Yuan, X., *et al.*	What Is the Importance of Two- and Three-Dimensional Site Effects? An Investigation of Single-Station Earthquake Records. **Pilz, M.**, Zhu, C., Cotton, F.
10:45 AM	Non-linear Simulation of the 2020 Beirut Explosion: Energy Coupling at Ground-air-sea Interfaces, Cratering, Hydroacoustic and Seismoacoustic Conversion and Signatures. **Ezzedine, S. M.**	High-frequency Emissions From Stimulation Microearthquakes in the Ambient Crust. Malin, P. E. A., **Zimakov, L. G.**, Leary, P. C.	STUDENT: Multidimensional Site Effects at the Treasure Island Downhole Array Using Seismo-VLAB and a Site-specific 3D Model. **Hallal, M. M.**, Cox, B. R., Asimaki, D., Ayoubi, P.
11:00 AM	Quantifying the Impact of Simulation Frequency Fidelity on Waveform-based Bayesian Inference for Seismic Monitoring Using Bayesian Experimental Design. **Catanach, T. A.**	Spatial-temporal Evolution of In-situ Vp/Vs Ratio in the Gofar Transform Fault Zone, East Pacific Rise. **Liu, T.**, Gong, J., Fan, W., Lin, G.	Characterization of Non-ergodic Site Effects at Selected Hard-rock Sites in Western Canada. **Hassani, B.**, Atkinson, G. M., Stewart, J. P., Fairhurst, M., Sheffer, M., *et al.*
11:30 AM–12:30 PM	*Plenary:* Frontiers in Seismology		
12:30–2:00 PM	Lunch Break		

Time	*Grand A*	*Grand B*	*Grand C*	*Grand E–K**
	Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1310).	**Adjoint Waveform Tomography: Methods and Applications** (see page 1200).	**Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation** (see page 1307).	**Structure and Seismogenesis of Subducting Slabs** (see page 1345).
2:00 PM	INVITED: Earthquake Detection in Northern California With Graph Neural Networks. McBrearty, I. W., **Beroza, G. C.**	Adjoint Tomography of the Hikurangi Subduction Zone and the North Island of New Zealand. **Chow, B.**, Kaneko, Y., Tape, C., Modrak, R., Mortimer, N., *et al.*	Kinematic Rupture Models of Listric Normal Faulting in Earthquake Ground Motion Simulations. **Pitarka, A.**, Scalise, M., Zeiler, C., Rodgers, A., Walter, W. R.	INVITED: The Role of Subducted Fluids in the Genesis of Deep Earthquakes: Evidence From Deep Diamonds and Subduction Zone Thermal Modeling. **Shirey, S. B.**, Wagner, L. S., Walter, M. J., Pearson, D. G., van Keken, P. E.
2:15 PM	Toward Integrating Machine Learning Phase Pickers Into the Southern California Seismic Network Earthquake Catalog. **Yoon, C.**, Tam, R., Andrews, J., Bhadha, R., Ross, Z. E., *et al.*	STUDENT: The Lithospheric Structures Beneath Central and Southern Appalachians Revealed by Joint Full-waveform Inversion of Ambient Noise and Teleseismic Data. **Lei, T.**, He, B., Wang, K., Du, N., Liu, Q.	The Dynamics of Unlikely Slip: 3D Dynamic Rupture Modeling of Low-angle Normal Fault Rupture at the Mai'iu Fault, Papua New Guinea. **Gabriel, A.**, Biemiller, J. B., Ulrich, T.	Metamorphism-facilitated Faulting in Deforming Orthopyroxene: Implications for Global Intermediate-depth Seismicity. **Wang, Y.**, Shi, F., Wen, J., Yu, T., Zhu, L., *et al.*
2:30 PM	On-premises Integration of Machine Learning Models at UUSS—Distributed Computing and Messaging. **Baker, B.**, Armstrong, A., Pankow, K. L., Koper, K. D.	STUDENT: SASSY21: A 3D Seismic Structural Model of the Lithosphere and Underlying Mantle Beneath Southeast Asia from Multi-scale Adjoint Waveform Tomography. **Wehner, D.**, Blom, N., Rawlinson, N., Daryono, S., Miller, M. S., *et al.*	Exploring Fault Segmentation and Rupture Length on the Sierra Madre Fault Zone With Dynamic Rupture Simulations. **Lozos, J.**	Scaling Relations Between High Pressure, High Temperature Transformational Faulting Experiments and Natural Seismicity. **Officer, T.**, Zhan, Z., Zhu, L., Yu, T., Wang, Y.
2:45 PM	Event-based Training in Label-limited Regimes. **Linville, L.**	WUS256: An Adjoint Waveform Tomography Model of the Western United States for Improved Waveform Simulations. **Rodgers, A.**, Krischer, L., Afanasiev, M., Boehm, C., Doody, C. D., *et al.*	STUDENT: The Effects of Precursory Seismic Velocity Changes on Earthquake Sequence Simulations. **Thakur, P.**, Huang, Y.	STUDENT: Using High Frequency Mode-converted Phases at the Plate Interface to Characterize the Properties and Along-strike Variability of the Alaska-Aleutian Subducting Plate. **Daly, K. A.**, Abers, G. A.

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy (see page 1210).	**Advances in Seismoacoustic Methods for Explosion Monitoring** (see page 1223).	**Site Response Characterization in Seismic Hazard Analysis** (see page 1338).
2:00 PM	STUDENT: Strawberry Mountains Slip Rates in Suspiciously Seismically Still Eastern Oregon. **Dunning, A.**, Streig, A. R., Madin, I., Amidon, W., Balco, G., *et al.*	Mine Explosion Identification Using Machine Learning Methods. **Rabin, N.**, Bregman, Y., Niv, I.	Site Characterization of Seismic Stations in Metropolitan Lima, Peru. Gonzales, C., **Moya Huallpa, L. A.**, Ccahua, A., Lazares, F., Yamazaki, F., *et al.*
2:15 PM	Deep Coseismic Slip in the Cascadia Megathrust Can Be Consistent with Coastal Subsidence. **Melgar, D.**, Sahakian, V. J., Thomas, A. M.	An Alternative Multi-processor Configuration for Network Processing at the CTBTO. **Le Bras, R. J.**, Kushida, N., Strachota, P., Ali, S., Miljanovic-Tamarit, V.	STUDENT: Reducing the Epistemic Uncertainty in Ground Motion Prediction Equations by Incorporating Site Fundamental Frequency Using Japanese Stations in NGA-West2 Database. **Yazdi, M.**, Motamed, R., Anderson, J. G.
2:30 PM	STUDENT: Interseismic Deformation in the Dead Sea Fault Region Inferred by InSAR and GNSS Measurements. **Golriz, D.**, Hamiel, Y., Bock, Y., Xu, X., Sandwell, D. T.	Near Field Modeling of the Large Surface Explosion Coupling Experiment (LSECE). **Vorobiev, O.**, Ford, S. R., Walter, W. R.	STUDENT: A Practical Approach for Accounting for Vs Spatial Variability Using 1D Site Response Analyses. **Pretell, R.**, Ziotopoulou, K., Abrahamson, N.
2:45 PM	INVITED: Earthquake Behaviors in Earthquake Cycle Simulations With Fault Damage Zones. **Huang, Y.**, Thakur, P.	A New Approach for Simulating Sound Wave Propagation Based on Lab Experiments Using 3D-printed Models. **Wang, J.**, Park, S.	STUDENT: Linear Site Response of Soft Peaty Organic Soil Sites in California's Bay-Delta Region. **Buckreis, T. E.**, Wang, P., Brandenberg, S. J., Stewart, J. P.

Time	Grand A	Grand B	Grand C	Grand E–K*
	Network Seismology: Recent Developments…	**Adjoint Waveform Tomography…**	**Multi-scale Dynamics of Complex Earthquake…**	**Structure and Seismogenesis …**
3:00 PM	Nodal Deployments and Their Role in Regional Seismic Monitoring. **Walter, J.**, Ogwari, P. O., Chen, X.	STUDENT: The Collaborative Seismic Earth Model: Generation 2. **Noe, S.**, van Herwaarden, D., Thrastarson, S., Masouminia, N., Böhm, C., *et al.*	Dynamic Off-fault Failure and Tsunamigenesis at Strike-slip Restraining Bends. **Ma, S.**, Du, Y.	STUDENT: Complex Structure in the Nootka Fault Zone Revealed by Double-difference Tomography and a Newly Determined Earthquake Catalog. **Merrill, R.**, Bostock, M., Peacock, S. M., Schaeffer, A., Roecker, S.
3:15 PM–4:30 PM	Poster Break			
		Adjoint Waveform Tomography: Methods and Applications (see page 1200).		**Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes** (see page 1230).
4:30 PM		A New Model of the Australasian Region From Adjoint Tomography. **Boehm, C.**, Afanasiev, M., Krischer, L., van Driel, M., Fichtner, A.		Deep-learning-based Earthquake Catalog Production at Axial Seamount From 2014 to 2021. **Wang, K.**, Waldhauser, F., Tolstoy, M., Wilcock, W. S. D., Tan, Y., *et al.*
4:45 PM		STUDENT: Using K-means Clustering to Compare Adjoint Waveform Tomography Models of California and Nevada. **Doody, C. D.**, Rodgers, A., Boehm, C., Afanasiev, M., Krischer, L., *et al.*		STUDENT: Hydroacoustic Investigation of Lava-water Interactions During the 2018 Kilauea Eruption. **Atkins, C. M.**, Costa, O., Caplan-Auerbach, J.
5:00 PM		STUDENT: Regional Experiments on Source-encoded Adjoint Waveform Tomography. **Cui, C.**, Tromp, J., Bachmann, E., Peter, D. B.		Low-frequency Seismicity Registered at Ceboruco Volcano, Mexico. **Núñez, D.**, Núñez-Cornu, F. J., Rowe, C. A.
5:15 PM		STUDENT: Accelerating Full Waveform Modeling and Inversion With Neural Operators. **Yang, Y.**, Gao, A. F., Castellanos, J. C., Ross, Z. E., Azizzadenesheli, K., *et al.*		Recent Eruptive Activity of Sangay Volcano Observed by an Infrasound Array. **Ruiz, M. C.**, Acero, W., Hernandez, S., Palacios, P., Angelis, S. D., *et al.*

Time	*Cedar**	*Regency A–C*	*Regency E–G*
	Advances in Earthquake Geology…	**Advances in Seismoacoustic…**	**Site Response Characterization in Seismic Hazard Analysis**
3:00 PM	STUDENT: Juicy Data — Preliminary Results From a Drone Lidar System Applied to Tectonic Geomorphology. **Salomon, G.**, Finley, T., Stephen, R., Nissen, E.	Verifying the Presence of an Acoustic Duct Using Balloon-borne Infrasound. **Albert, S. A.**, Bowman, D. C., Dannemann Dugick, F. K., Silber, E. A.	Nonlinearity of the Vertical Ground Motion Component. **Kamai, R.**, Frid, M., Baram, A.
3:15 PM–4:30 PM	Poster Break		
	Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy (see page 1210).	**Network Seismology: Recent Developments, Challenges and Lessons Learned** (see page 1310).	**Frontiers in Marine Seismology** (see page 1288).
4:30 PM	Distributed Faulting and Off-fault Deformation Revealed by Optical Image Correlation Using Unmanned Aerial Vehicle Imagery of the 2019 Ridgecrest Earthquake Sequence. **Chupik, C.**, Jobe, J. A. T.	INVITED: Learning Lessons and Sharing Solutions With ANSS NetOps Workshops. **Biasi, G.**, Withers, M., Bhadha, R.	STUDENT: Microplate Evolution in the Queen Charlotte Triple Junction and Explorer Region: New Insights from Microseismicity. **Littel, G.**, Bostock, M., Schaeffer, A., Roecker, S.
4:45 PM	Continued Building of STEPS: Slip Time Earthquake Path Simulations. **Hatem, A. E.**, Briggs, R. W., Gold, R., Scharer, K., Minson, S. E., *et al.*	Data Mining a Large Station Metrics Database to Guide Station Siting. **Hutko, A.**, Marczewski, K., Ulberg, C., Hartog, R.	Rapid Formation of Pack Ice in Shallow Coastal Waters, as Observed by Seafloor Distributed Acoustic Sensing. **Baker, M. G.**, Abbott, R. E.
5:00 PM	STUDENT: The Mechanics and Frequency of Joint Earthquake Ruptures of the San Andreas and San Jacinto Faults. **Rodriguez Padilla, A. M.**, Oskin, M. E., Rockwell, T. K., Delusina, I., Singleton, D. M.	An Overview of Quality Assurance Efforts at the Alaska Earthquake Center. **McFarlin, H.**, Ruppert, N., Holtkamp, S., Murphy, N., West, M. E.	STUDENT: OBS Noise Reduction Using Harmonic-percussive Separation Algorithms. **Zali, Z.**, Rein, T., Krüger, F., Ohrnberger, M., Scherbaum, F.
5:15 PM	INVITED: Constraining a Long History of Paleolake and Paleoearthquake Activities Using Deep Boreholes at the Ancient Lake Cahuilla, Coachella, California. **Saha, S.**, Argueta, M. O., Moon, S., Rockwell, T. K., Scharer, K., *et al.*	Posthole N4: Potential Improvements in Data Quality and Station Reliability From Posthole Versus Vault Installations. **Wolin, E.**, Anderson, J., Roberts, S., Patton, J. V., Ploetz, S., *et al.*	Novel Autonomous and Cabled OBS Solutions for Offshore Seismic Research. **Lindsey, J. C.**, Reis, W., Watkiss, N., Hill, P., Cilia, M.

Time	Grand A	Grand B	Grand C	Grand E–K*
		Adjoint Waveform Tomography…		**Advances in the Use of Seismic and Acoustic….**
5:30 PM		Automatic Differentiation for Seismic Inversion. **Zhu, W.**, Xu, K., Darve, E., Biondi, B., Beroza, G. C.		STUDENT: Matched Filter Detection of Lava Lake Seismicity Using a Dense Short Period Network on Mount Erebus Volcano. **Jaski, E.**, Aster, R., Grapenthin, R., Chaput, J.

Poster Sessions

Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions (see page 1286).

1. STUDENT: Exploring Potential Causes for Observed Overprediction of Ground Shaking by USGS Hazard Maps Relative to Historical Shaking Data. **Gallahue, M.**, Salditch, L., Lucas, M. C., Neely, J., Stein, S., *et al.*
2. A Comparison of Foraminifera and Diatom-based Transfer Function Estimates of Coseismic Subsidence During the 1700 CE Earthquake Along the Oregon Coast. **Dura, T.**, Hemphill-Haley, E., Cahill, N., Kelsey, H. M., Hawkes, A., *et al.*
3. STUDENT: Diatom-based Quantification of Coseismic Land-level Change From Cascadia Subduction Zone Earthquakes in Southern Oregon. **Bruce, D.**, Dura, T., Witter, R. C., Kelsey, H. M.
4. The Cascadia Offshore Paleoseismic Record: A Visual Tour of the Systems Approach and Some Updates. **Goldfinger, C.**, Hamilton, T. S., Enkin, R. J., Patton, J. R.
5. Stochastic Tsunami Modeling Including Source Kinematics. **Riquelme, S.**, Fuentes, M.
6. Tsunami Generated From Asteroids Impacting Earth's Oceans: Consequences on Coastlines of USA for Disaster Response and Management Preparedness. **Ezzedine, S. M.**, Syal, M., Dearborn, D., Miller, P.

New Developments in Physics- and Statistics-based Earthquake Forecasting (see page 1319).

7. Phebus: A Full Bayesian Workflow to Estimate Earthquake Recurrence Parameters and Uncertainties for Seismic Hazard Models. **Duverger, C.**, Keller, M., Senfaute, G.
8. STUDENT: Ranking Earthquake Forecasts Using Proper Scoring Rules: Binary Events in a Low Probability Environment. **Serafini, F.**, Naylor, M., Lindgren, F., Werner, M. J., Main, I.
9. A New Seismic Moment Magnitude (Mwg) and Moment Magnitude (Mw): Common Root and Differences. **Das, R.**, Meneses, C., Gonzalez, G.
10. Assessing the Predictive Skills of Global and Regional Earthquake Forecasting Models for California, Italy and New Zealand. **Bayona, J.**, Savran, W. H., Werner, M. J.
11. pyCSEP: A Python Tool-kit for Earthquake Forecast Developers. **Savran, W. H.**, Bayona, J., Iturrieta, P., Asim, K., Bao, H., *et al.*
12. STUDENT: An Interactive Web Tool to Visualize and Improve USGS Operational Aftershock Forecasts. **Paris, G. M.**, Michael, A. J.

Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1312).

13. STUDENT: Evaluation of MEMS Sensor Reliability Through Comparative Analysis of Seismic Records and Field Experiment Using 2021 Jeju Earthquake. **Jang, D.**, Kim, M., Yoo, B., Kwak, D.
14. The Colorado Geological Survey Seismic Network, Collaboration and Outreach. **Bogolub, K. R.**, Morgan, M., Fitzgerald, F. S., Broes, L. D., Radach, K. C.
15. System Monitoring During Stressful Times. **Bhadha, R.**, Stubailo, I., Bruton, C. P., Biasi, G., Watkins, M. B., *et al.*
16. Swiss Shakemap at Fifteen: Distinctive Local Features and International Outreach. **Cauzzi, C.**, Clinton, J. F., Kästli, P., Fäh, D., Bergamo, P., *et al.*
17. Mission-critical Real Time Data Acquisition: An Earthquake Early Warning Case Study. Laporte, M., Perlin, M. M., Tatham, B., **Pelyk, N.**
18. The Community Seismic Network (CSN): 1000 Stations in the Los Angeles Basin. **Clayton, R. W.**, Kohler, M., Heaton, T. H., Guy, R., Bunn, J., *et al.*
19. Idaho National Laboratory Seismic Monitoring Program. **Bockholt, B.**

Time	Cedar*	Regency A–C	Regency E–G
	Advances in Earthquake Geology: Spatiotemporal Variations…	**Network Seismology: Recent Developments…**	**Frontiers in Marine Seismology**
5:30 PM	Student: Do Earthquakes Rupture Through Releasing Bends in the Western Nepal Fault System? **Curtiss, E.**, Bemis, S., Murphy, M., Taylor, M., Styron, R., *et al.*	Raspberry Shake Citizen Seismological Network. **Blanco, J. F. C.**, Christensen, B.	SMART Repeaters: Sensor-enabled Submarine Fiber Optic Repeaters for Multi-scale and Multi-use Monitoring and Observing. **Fouch, M. J.**, Lentz, S. T., Howe, B. M., Avenson, B.

20. Student: Aftershock Relocations Using Nonlinear Inversion, 1D and 3D Velocity Models and Machine Learning to Image Fault Structure. **Wells, D.**, Baker, B., Pankow, K. L.
21. Digital Radio Telemetry Issues in Network Seismology. **Rusho, J. A.**, Trow, A. J., Forbes, N. M., Alexander, J.
22. Arizona's Seismic Network: A Case Study in Balancing Growth, Risk and Resources. **Ben-Horin, J. Y.**, Peavey, H.
23. Caravel: A New Seismic Monitoring System. **Scognamiglio, L.**, Bono, A., Lauciani, V., Quintiliani, M., Battelli, P., *et al.*
24. QuakeSaver: Smart Seismic Sensors and Fleet Management. **Isken, M. P.**, Kriegerowski, M., Dolling, M.
25. The Advanced National Seismic System ComCat Earthquake Catalog: Nine Years of Amassing Earthquake Source Parameters and Impact Data. **Earle, P.**, Ambruz, N. B., Benz, H. M., Yeck, W. L., Fee, J. M., *et al.*
26. Earthworm and AQMS for Earthquake Data Acquisition and Management in the Cloud at the California Strong Motion Instrumentation Program. **Friberg, P. A.**, Hadaddi, H., Hagos, L., Branum, D., Gold, M., *et al.*
27. Determining Seismic Station Timing Accuracy Using Regional Stations. **Wilson, D. C.**, Wolin, E., Storm, T., Ringler, A. T.
28. ISC Datasets for Seismology. **Storchak, D. A.**, Harris, J., Di Giacomo, D., Garth, T., Team, I.
29. Improving the Reliability of the Alaska Earthquake Center's Field Monitoring Networks. **Murphy, N.**, Ruppert, N., McFarlin, H., Place, M., Reynolds, M., *et al.*
30. Ensuring Timing From Nodal and Network Seismic Systems Is Synchronized. **Zeiler, C.**, Turley, R., Scalise, M., White, R., Caylor, J.
31. Use of the SCARDEC Method for Monitoring and Research Applications. **Vallee, M.**
32. Student: Pyrocko—A Versatile Software Framework for Seismology. Heimann, S., **Isken, M. P.**, Kriegerowski, M., Nooshiri, N., Petersen, G., *et al.*
33. Student: Pyrocko—The Other Seismology Toolbox in Python. Heimann, S., Kriegerowski, M., Isken, M. P., Nooshiri, N., Petersen, G., *et al.*
34. Student: Visualizing Global Seismic Phases With AlpArray. **Ling, A.**, Stähler, S. C., Giardini, D.
35. Denoising Seismic Waveforms Using the Continuous Wavelet Transform. **Aguiar, A. C.**, Chiang, A., Myers, S. C.

Distributed Deformation from Surface Fault Rupture (see page 1251).

41. New Constraints on the Location and Subsurface Structure of the Holocene Birch Bay Fault, Northwestern Washington, USA. **Duckworth, W. C.**, Zaleski, M. P., Zellman, M., McClymont, A. F.
42. Paleoseismic Evidence for a Near Historic Rupture within the Seattle Fault Zone. **Angster, S.**, Sherrod, B. L., Pearl, J. K., Johns, W.

Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation (see page 1308).

43. Student: Investigating the Effects of Fault Dip Angle on Rupture Propagation Along Branch Fault Systems using 3D Dynamic Rupture Simulations. **Marschall, E.**, Douilly, R.
44. The Ingredients Needed for Realistic Dynamic Earthquake Rupture Simulations. **Harris, R.**
45. Student: Revisiting the 1906 M 7.1 Meishan, Taiwan, Earthquake: A Dynamic Rupture Modeling Perspective on Single-fault Versus Multi-fault. **Lin, C.**, von Specht, S., Ma, K.
46. Peculiar Rupture Path of the 2019 Peru Intraslab Earthquake Suggests a Key Role of the Surface-reflected Dynamic Stresses. **Vallee, M.**, Xie, Y., Grandin, R., Villegas, J., Nocquet, J., *et al.*
47. High-frequency Ground-shaking Variability From Rough-fault Ruptures. **Vyas, J.**, Galis, M., Mai, P.

48. Calibration of Subsurface Dynamic Parameters and Fault Geometry From Surface Fault Rupture Observations: An Example From the Shallow 2019 mw4.9 Le Teil, France, Event. Sassi, R., **Hok, S.**, Klinger, Y., Delouis, B.

Site Response Characterization in Seismic Hazard Analysis (see page 1341).

49. Within-site Variability in Earthquake Site Response. **Zhu, C.**, Cotton, F., Kwak, D., Ji, K., Kawase, H., *et al.*
50. Student: Minimizing Geophysical Site Characterization Procedures to Estimate Vs30 Through the Use of Vr40. **Gomez, J.**, Yong, A., Hayashi, K., Martin, A., Kottke, A., *et al.*
51. Student: Evaluation of Modified Simplified Equations for Estimating Kinematic Soil-structure Interaction Effects in Buildings With Large Footprints and Embedment Depths: A Finite Element Approach. **Boushehri, R.**, Zogh, P., Motamed, R.
52. Student: Vs30 Site Characterization Near the Strong-motion Recording Site at Fremont Central Park, California, Using S-wave Refraction Tomography and Multichannel Analysis of Surface Waves Methods. **Gomez, A. J.**, Catchings, R. D., Goldman, M. R., Chan, J. H., Criley, C. J., *et al.*
53. Modeling of the Surface-to-depth Spectral Amplification in 3D Media. **Oprsal, I.**, Hallo, M., Fäh, D., Burjanek, J.
54. Future Directions of the COSMOS Site Characterization Committee. **Pilz, M.**, Askan, A., D'Amico, S.
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Abstracts of the Annual Meeting

The 15 January 2022 Tonga Eruption and Tsunami

Oral Session · Thursday 21 April · 8:00 AM Grand C

Conveners: Peggy Hellweg, University of California, Berkeley; Lori A. Dengler, Humboldt State University; Emile A. Okal, Northwestern University; Seth Moran, U.S. Geological Survey; Stuart Weinstein, PTWC; Summer Ohlendorf, NTWC

USGS Seismic Monitoring of the 2022 Hunga Tonga-Hunga Haʻapai Volcano Eruption

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The USGS National Earthquake Information Center (NEIC) often responds to seismic events beyond its core global earthquake monitoring mission. A recent example is NEIC's response to the 2022 eruption of Hunga Tonga-Hunga Haʻapai Volcano. NEIC worked closely with the USGS Volcano Disaster Assistance Program (VDAP) to help estimate future volcanic hazards by monitoring the ongoing earthquake sequence following the eruption. NEIC's automatic systems were unable to detect many of the smaller, often emergent, seismic events. To provide VDAP with actionable information, methods were rapidly developed to detect, locate and publicly disseminate events in the sequence. Processing approaches included periodic visual scanning of seismic waveforms and the implementation of waveform cross correlation detection techniques. NEIC's ability to provide critical supporting information to VDAP and its partner agencies was greatly enhanced by close collaboration between NEIC researchers, developers, operational staff and external collaborators. The productive sequence started with 14 locatable events ~M4.5 and larger on the first day following the January 15th eruption, followed by a day-long lull in seismicity and then an increased rate to roughly 10 events per day for the following four days. Seismicity at or above the M4.5 level had ceased by February 16th. Cross-correlation techniques revealed more events, many of which were too small to obtain quality locations and thus are not included in the NEIC catalog. Single-event locations using standard catalog processing techniques are dispersed over an area of 1500 km^2; however, subsequent multi-event surface-wave relocations show the events are likely concentrated within an area of 25 km^2. Preliminary results show a migration of seismicity towards the southeast in the days following the eruption. We will discuss details of our near real-time response, post processing detections and insights gained from event relocations.

Seismological Characterization of Dynamic Parameters of the Hunga Tonga Explosion From Teleseismic Waves

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Most of the largest volcanic activity in the world occurs in remote places as deep oceans or poorly monitored oceanic islands. Thus, our capacity of monitoring volcanoes is limited to remote sensing and global geophysical observations. However, the rapid estimation of volcanic eruption parameters is needed for scientific understanding of the eruptive process and rapid hazard estimation. We first a method to rapidly identify large volcanic explosions, based on analysis of seismic data. The method automatically detects and locate long period (0.01-0.03Hz) signals associated with physical processes close to the Earth surface, by analyzing surface waves recorded at global seismic stations. With this methodology, we promptly detect the January 15, 2022 Hunga Tonga eruption, among many other signals associated with known and unknown processes. We further use the waves generate by the Hunga Tonga volcanic explosion and estimate important first-order parameters of the eruption (Force spectrum, impulse). We then relate the estimated parameters with the volcanic explosivity index (VEI). Our estimate of VEI~6, indicate how the Hunga Tonga eruption is among the largest volcanic activity ever recorded with modern geophysical instrumentation and can provide new insights about the physics of large volcanoes.

Seismic Characterization of the 2022 Hunga Tonga-Hunga Haʻapai Volcanic Eruption.

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The submarine eruption of Hunga Tonga-Hunga Haʻapai (HTHH) volcano on January 15th, 2022 has attracted a substantial amount of attention due to the severity of the tsunami that struck the Tonga Islands and the exceptional nature of the atmospheric perturbation from the eruption. We present a study of the seismic source characteristics of the peak eruptive phase. We performed a full moment tensor inversion of the main Mw 5.8 event that occurred during the peak phase of the eruption, at 04:15 UTC, as it is the largest identified seismic event that occurred during the eruption. Due to the poor signal-to-noise ratio in the long-distance data that prevent us from using body-wave signals, we focused on the Rayleigh and Love waveforms to perform our inversion. We tested our method on shallow earthquakes from the GCMT catalog that are close to HTHH and recorded by the same set of stations. The result of our inversion is a shallow isotropic moment tensor, which indicates the explosive nature of this event and seems to corroborate the satellite observations and the strong acoustic signal recorded and heard around the globe. We also highlight the temporal complexity of the source of this event by inverting for the first sub-event immediately following the main explosion, which suggests that the overall magnitude of this event has been initially underestimated. The estimated source time function allows us to perform a joint full moment tensor inversion of the two main pulses, yielding two repeated shallow explosive sources that precede the long-lasting signals, observed across the whole network. Our complete analysis of magnitude, moment tensor source type, depth and source time function enables an accurate estimation of the uncertainty of the magnitude of the event, as well as tradeoffs among different source parameters.

The Global Seismographic Network Reveals Atmospherically Coupled Normal Modes Excited by the 2022 Tonga Eruption

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The eruption of submarine volcano Hunga Tonga-Hung Haʻapai (Tonga) on January 15, 2022, UTC was one of the largest eruptions recorded by modern geophysical instrumentation and was recorded globally at 112 stations across the Global Seismographic Network (GSN) on seismometers, microbarographs and infrasound sensors. The broadband instrumentation in the GSN allows us to make high fidelity observations of the excitation of fundamental solid Earth normal modes including several near 3.7 and 4.4 mHz. Similar modes were observed seismically following the 1991 Pinatubo volcanic eruption and have since been interpreted to arise through excitation of acoustic fundamental modes of the atmosphere which couple into the solid Earth. We compare solid Earth modes between the Tonga eruption and Pinatubo VEI 6 eruption and find that, although both eruptions strongly excited the normal mode ${}_0S_{29}$ (3.72 mHz), the amplitude of that mode was roughly 11 times larger for the 2022 Tonga eruption. GSN microbarograph records also reveal direct observations of the acoustic fundamental mode of the atmosphere. These pressure oscillations begin about 40 minutes following the eruption,

occur concurrently and in-phase with Rayleigh wave excitation and are only observed on microbarographs in close (< 1000 km) proximity to the eruption. Therefore, these fundamental observations recorded by multiple instruments across the globe will improve our understanding of how atmospheric modes are excited by volcanic eruptions or explosions and how these modes couple into the solid Earth.

Early Episodic Eruption Characteristics of the January 2022 Hunga Tonga-Hunga Ha'apai Volcanic Activities

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The paroxysmal eruption of Hunga Tonga-Hunga Ha'apai (HTHH) on 15 January 2022 began ~04:01 UTC and produced an M5.8 seismic event at 04:15:45 UTC as reported by USGS. To understand the eruption characteristics, we stacked globally recorded seismograms based on the moveout of teleseismic P waves generated by the M5.8 event. Within five minutes of the 04:15:45 UTC event, we identified at least four distinct episodic subevents (E-1, E-2, E-3 and E-4) that occurred as the volcanic plume grew from 25 km (~04:15 UTC) to ~ 35 km (04:20 UTC), preceding the extreme plume height of 58 km by ~15 minutes. These subevents have similar durations of ~ 25 s, but subevents E-2, E-3, and E-4 are ~204.6 s, ~39.8 s and ~25.4 s after E-1, E-2, E-3, respectively. We call these subevents 'episodic' due to waveform similarities. Stacking the direct S waves yields no SH energy, suggesting azimuthally symmetric source mechanism and no landslide or induced earthquakes. Each subevent is characterized by four distinct eruptive stages: Stage-1/2/3/4 are ~3s/15s/3s/3s in duration and correspond to down/up/down/up far-field seismic ground velocities. Stage-1 might be a precursor to the main eruption in Stage-2, possibly due to the rocket-type explosive eruption, with a peak force of 1.1e13 N. Stage-3/4 could be cyclic rebounds of vertical forces related to the magma chamber motion. After Stage-4, a gradual recovery phase is characterized by oscillating ground motion until the next subevent begins. Full-waveform seismic modeling finds that a vertical single-force mechanism in all 4 stages better explains the data. That the early phase of the violent HTHH eruption is composed of four similar episodic subevents separated in time by tens of seconds may be indicative of rapid changes in the configuration of the shallow magma transport system associated with the instantaneous discharge of up to 1e6 m^3/s required to support the observed, 58 km high volcanic plume.

What Produced the Giant Hunga Tonga-Hunga Ha'apai Eruption Cloud?

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The January 15, 2022, Hunga Tonga Hunga-Ha'apai eruption produced the largest umbrella cloud since the 1991 eruption of Mt. Pinatubo. Infrared data from the Himawari–8 and GOES–17 geostationary satellites show that, starting around 0415 UTC, the umbrella cloud expanded at heights of 25–35 km above sea level (asl) with an overshooting top that may have reached 55 km asl. Over the first 50 minutes, the cloud radius R grew to ~200 km, following a growth relationship with time t approximated by $R \sim t^{2/3}$. This extreme growth rate suggests an average volume flux of particles, gas and entrained air of 300-500 km^3/s. We used a one-dimensional model of plume rise in local atmospheric conditions to approximately reproduce the observed umbrella height and volume flux with a mass eruption rate of solids (MER) of about 3.3e09 kg/s. This rate is several times greater than the Pinatubo eruption and would imply ejection of several km^3 dense-rock equivalent (DRE) of magma over just the first hour of eruption. Using these source parameters, we modeled tephra dispersal and found that an 8 km^3 DRE eruption should produce tens of centimeters (cm) of tephra at Tongatapu, 65–75 km SE of the volcano. However, only a few cm were reported there. In addition, the SO_2 emitted (~0.4 Tg) was 10-50x smaller than expected for an eruption of 8 km^3 DRE (S. Carn, written commun.) Many volcanologists have speculated that entrained seawater enhanced the umbrella growth rate; however, our 1-D plume modeling indicates that addition of seawater would have the opposite effect. Addition of >50 wt% magmatic gas could produce the 300–500 km^3/s volume flux with an MER<1e09 kg/s; however, that would require an implausibly large (>10 km^3) gas reservoir at 2-4 km depth. Such inconsistencies could in part be due to our use of a 1-D plume model; it is likely that understanding the origin of this giant cloud will require more complex modeling, as well as more field study of the eruption deposits.

Seismic, Infrasound and Hydroacoustic Analysis of the 2022 Tonga Eruption

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Regional low-frequency (f) surface-waves and teleseismic P-waves from the 2022-01-15 Tonga eruption reveal a series of at least 4 shallow (depth < 2*km*) seismic events. A full moment tensor inversion was performed to estimate the origin-time (OT), moment magnitude (M_w) and source mechanism. The 1st event occurred at OT=04h:04m:02s with a M_w=5.25 CLVD mechanism. The 2nd event occurred at OT= 04h:15m:31.5s with a M_w=5.82 explosion mechanism. This was followed 3.5 mins later by 2 additional overlapping events with similar magnitudes and explosion mechanisms of ~ M_w=5.56. The CLVD of the 1st event is likely the result of magma venting 11 *mins* prior to the eruption. The subsequent eruption was composed of at least 3 events with explosion mechanisms. Rough estimates from the combined seismic moment would put the explosive yield at about 5 *MT*. The Green's functions used in the inversions were calibrated using the Central Lau Basin 1D velocity model for paths to GSN/G net stations FUNA, MSVF and FUTU, and a Pacific Plate model for RAR (*Crawford et al.*, 2003). Analysis and modeling of low-f teleseismic P-waves from the 2nd event reveal additional phases from the 3rd and 4th events that cannot be explained by predicted PP and PPP travel-time curves. This supports multiple shallow sources with rise times of 20 *s* and isotropic radiation patterns. Seismograms were deficient in high-f due to long source rise-times and blockage from oceanic crust. The Tonga eruption also produced atmospheric pressure disturbances propagating as gravity waves and infrasound. We investigated propagation characteristics of the infrasound signals using finite-difference simulations including full 3D weather forecast model and estimated acoustic energy associated with the eruption process. Hydroacoustic signals were detected using a F-detector between 2-8 *Hz* at IMS stations Juan Fernández Island (HA03) and Wake Island (HA11). Weak signals were likely due to blockage by the Tonga-Kermadec Ridge.

Air Waves From the 2022 Tonga Explosion: Theoretical Studies and an Oversight in the Reporting of DART Sensor Data

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The 2022 Tonga explosion generated gravito-acoustic air waves recorded worldwide, including multiple passages, by atmospheric pressure sensors, onland seismometers, tide gauges and ocean-bottom pressure sensors. It also generated genuine tsunami waves, observed in the Pacific and Indian Ocean. As described by Harkrider & Press [1967] in the case of Krakatau (1883), the world-wide "tsunami" observed by tidal gauges is actually an ancillary prolongation of the eigenfunction of the airwave into the water column when it travels over an oceanic basin. We study theoretically the structure of the airwave (with or without an ocean layer) in the flat-layered formalism of these authors, as well as in the spheroidal mode one, introduced for regular tsunamis by Ward [1980] and in the case of atmospheric waves by Lognonné et al. [1999]. We find that the most robust component of the eigenfunction, largely insensitive to the presence of a water layer, is the overpressure in the lower atmosphere. The dynamic response, i.e., the vertical deformation of the sea surface in response to the overpressure, is strongly dependent on the local water depth and approaches the classical hydrostatic value of 1 cm/mbar only for a ~5-km deep ocean. It falters quickly in shallow seas, as veriified on tidal records across the Bering Sea. Similarly, the ratio of wave amplitude at the surface to overpressure at the bottom of the ocean (as measured, e.g., by a DART sensor) is also a function of water depth (and frequency), which does

not exceed 0.6 cm/mbar and can be much smaller in shallow seas. In this context, the present practice by the DART network of reporting their data directly as equivalent water heights (which was valid for genuine tsunamis under the SWA) is erroneous in the case of ocean-couple airwaves and can lead to inexact interpretation of sea surface displacements. We urge the DART program to report their data in true pressure units. Finally, the normal mode formalism allows the quantification of the source, tentatively described as an explosive moment of ~(0.5 to 2) 10**25 dyn*cm at an altitude of ~3.5 km.

The 15 January 2022 Hunga Tonga-Hunga Ha'api (HTHH) Explosive Eruption and the Challenges It Presented to the Pacific Tsunami Warning Center (PTWC)

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The tsunamis due to the eruption of HTHH presented the greatest challenge faced by the PTWC in nearly 20 years. This complex event was perhaps the first eruption of its kind since Krakatau in 1883 with several tsunami-generating mechanisms. The lack of available seismic and sea-level data along the Tonga-Kermadec Trench made it difficult to quickly understand what transpired in real-time. Current tsunami warning systems are primarily tuned for tsunamis generated by earthquakes, their most common cause. Therefore, neither of PTWC's two forecasting tools are designed for volcanic sources. The PTWC-developed RIFT model uses a WCMT and the Okada model to estimate seafloor displacement, shallow water wave equations to forecast deep-water wave propagation and Green's Law to estimate coastal runup. However, PTWC had no way to appropriately characterize the HTHH eruption source. PTWC also uses the PMEL/NCTR SIFT model, based on MOST, that can invert DART data to determine the slip distribution of subduction-zone earthquakes. PTWC could not invert DART measurements for a volcanic source mechanism either. Sea-Level data from Rarotonga, French Polynesia and New Zealand established that at least two tsunamis were generated: a tsunami triggered by an atmospheric pressure front that propagated at the speed of sound and a shallow-water gravity-wave tsunami that was generated at or near the source. PTWC had developed tools and products for the Caribbean Sea to address the possibility of tsunamis generated by eruptions at St. Lucia and Kick 'em Jenny. These products provide guidance based on sea-level observations alone. PTWC also developed a tsunami detector using coastal sea-level data for this situation, which it operationalized for HTHH after the 13 January eruption. We will present a brief timeline of events and actions taken by the PTWC. We will also discuss what stop-gap measures have been implemented should another eruption occur at HTTH and our plans for future response.

From a Boom and a Plume to Observation and Inundation: The US National Tsunami Warning Center's Unique Response to the Most Powerful Volcanic Tsunami Since Krakatoa

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The vast majority of tsunamis originate from offshore earthquakes, with coastal inundation occurring as soon as minutes after origin time. Given the short lead time to minimize loss of life and property, tsunami warning centers generally determine initial tsunami alerts using a suite of standing procedures based on earthquake parameters. Rare events like the volcanically-induced Hunga Tonga-Hunga Ha'apai tsunami test these largely earthquake-focused tsunami warning systems, challenging both their modeling and messaging capabilities. Here we outline the response of the U.S. National Tsunami Warning Center to the Hunga Tonga-Hunga Ha'apai tsunami, highlighting how the unique volcanic source impacted the center's tsunami modeling ability, decision-making and messaging. Over the hours following the main eruption, accumulating evidence from deep ocean pressure sensors (DARTs), coastal tide gauges and use of an earthquake-focused forecast model to judge tsunami scale led to the unusual decision to issue a Tsunami Advisory for the entire west coast of the continental U.S. and Canada (forecasted waves of 1-3 ft above the tide). To accomplish this, scientists made on-the-fly changes to a mostly automated earthquake-focused messaging system. Communication with partners focused on effectively conveying both event uncertainty and the real but moderate far-field coastal hazard. Facebook live feeds, wave and damage reports and reminders about the power of even a low amplitude tsunami were used to aid public understanding of this confusing event. The ad hoc approach to modeling and critical incident messaging were validated by Advisory-level tsunami observations in each western state and province. Though some of these areas experienced property and infrastructure damage, they saw no loss of life or significant injuries. This event underscores the tradeoffs in tsunami alerting between speed of response, flexibility and accuracy of modeling and messaging.

Using Infrasound and Umbrella Cloud Radius to Estimate the Size of the Hunga Tonga Eruption

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The Hunga Tonga eruption on 15 January 2022 generated strong infrasound waves that circulated the globe multiple times and produced a large umbrella cloud. The eruption began at 0414 UTC based on seismic data. Based on over 200 barometric and infrasound stations around the world, we estimated the size of the infrasound source using two schemes for reduced pressure, assuming 1/sqrt(r) for most of the path and different assumptions for the near field (< 100 km). We obtained estimates of 10-20 KPa and 100-200 kPa respectively. These are 1-3 orders of magnitude higher than comparable values for the eruptions of Okmok and Kasatochi in 2008, both of which were VEI=4. On that basis we estimated the likely VEI of the Hunga Tonga eruption to be VEI=5-6. Using satellite data, the umbrella cloud was estimated to have reached radii up to ~ 245 km. Using a recent formulation by Constantinescu et al. (2021), these radii also suggest a VEI=5-6. Strictly speaking, neither infrasound nor umbrella cloud radii are components of the original VEI. However, hazard managers need rapid assessments of the eruption dimensions. We think the time is right to incorporate modern geophysical data as criteria to estimate eruption intensity, and we therefore propose to estimate the VEI using seismic, infrasound, lightning, satellite remote sensing and any other data available within hours of an eruption. Companion studies are needed for each data set to determine relations to VEI. Final VEI estimates can wait until all data are available.

Water Level and Atmospheric Pressure Data From the Hunga Tonga-Hunga Ha'apai Tsunami: A Retrospective Analysis

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On January 15, 2022 the Hunga Tonga Hunga Ha'apai volcano erupted violently generating a significant tsunami that was observed around the world. This tsunami is the first volcanic source tsunami that has been observed worldwide by the modern tsunami instrument network. We observed that DART buoys (34) and tide gauges (480) recorded at least two distinct wave

groups when de-tided and band-pass filtered between 5-120 mins. The majority of sites observed an arrival with a phase speed between 350-320 m/s. We deduced that this arrival is likely to be an atmospheric Lamb wave from spectral analysis of the data. In addition to that analysis, we showed that pressure readings from within the planetary boundary layer show potential lamb wave behavior. We showed that the second wave group had a slower phase speed at ~150 m/s, which may be consistent with a submarine landslide source. However, our analysis has so far shown that this wave group appears at near-field stations only. We deduced that the observed worldwide tsunami is likely to have been generated by Proudman resonance with the atmospheric Lamb wave. Amplification of tsunami wave heights around the Pacific basin may be due to the combined effects of Proudman, Greenspan and shelf resonance. We compared these results with observations from DART buoys (22) and tide gauges (>10) that observed the Tohoku-oki tsunami.

The 15 January 2022 Hunga Tonga-Hunga Ha'apai Eruption as Recorded by MERMAID

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Mobile Earthquake Recording in Marine Areas by Independent Divers, MERMAIDs, are autonomous diving floats fitted with hydrophones that record the mid-column hydroacoustic wavefield from within the oceans. They are essentially floating seismometers that record seismoacoustic records of global earthquakes---and other noises in the oceans, such as volcanic eruptions---over repeated dive cycles. The primary data targeted by MERMAID are high-frequency (~1 Hz) teleseismic *P* waves useful for tomographic seismology of the deep mantle. These signals are identified in near real-time while at depth via an onboard detection algorithm, which also triggers MERMAID to ascend to the surface to transmit data segments that are roughly four minutes long within hours of rupture of large events. However, beyond those automatically windowed *P*-wave arrivals remain all the other data that MERMAID deems unworthy of automatic transmission, all of which remains retrievable from the MERMAID buffer for one year via two-way Iridium communication. Here we showcase one such data set, requested specifically in search of signals emanating from the 15 January 2022 eruption of Hunga Tonga-Hunga Ha'apai in the Tonga Islands. Our data are requested from floats in the South Pacific Plume Imaging and Modeling Array (SPPIM), a large array of some 50 MERMAIDs set adrift in the South Pacific beginning in 2018 and managed by the EarthScope-Oceans Consortium (see EarthScopeOceans.org for a real-time map of of the SPPIM array). Our floats, being at recording depths averaging 1500 m, are uniquely positioned to record the hydroacoustic signature of this large eruption. In this presentation we characterize the types of signals we are able to recover from the MERMAID buffer, assess signal amplitudes and spectra in relation to their ray paths and local bathymetry and analyze correlations between stations to characterize wavespeeds and investigate questions concerning eruptive directionality.

Hunga Tonga-Hunga Ha'apai: Spectral Characteristics of Traveling Ionospheric Disturbances From the January 2022 Eruption and Tsunami

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Hunga Tonga-Hunga Ha'apai violently erupted on January 15, 2022 approximately 65 km north of Tonga's main island in the South Pacific Ocean. Outlying islands were destroyed by the subsequent tsunami, which also flooded portions of western North and South America. Acoustic-gravity waves generated by both the eruption and tsunami caused complex ionospheric disturbances at both supersonic and subsonic propagation speeds. We present here the nature of these ionospheric disturbances using the time-differenced geometry-free combination of Global Navigation Satellite System observables. After integrating the time-differenced total electron content values, we band-pass the waveforms between 0.5-10 mHz and focus on satellites with sub-ionospheric distances less than 5000 km from the volcano, processing hundreds of ground stations in total. We find that traveling ionospheric disturbances were measured over Tonga, New Zealand and Hawai'i with filtered perturbation magnitudes over 5 TECu. To consolidate the data, we perform spatial resampling at 500 km intervals to find a median TEC time series to interrogate the nature of the ionospheric signals and then perform wavelet transforms to obtain the frequency dependence. We find that at a distance of approximately 2000 km, the acoustic pulse and tsunami generated gravity waves in the ionosphere separate from each other and have distinct max spectral periods. We then validate the arrival of tsunami generated ionospheric disturbances against deep-water DART buoy observations. We finish by discussing the implications for early warning systems and the need for multi-sensor monitoring during cascading hazards.

The Hunga Tonga-Hunga Ha'apai Eruption of 15 January 2022 Observed on the Multi-technology International Monitoring System Network

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The Hunga Tonga-Hunga Ha'apai volcano entered an active phase with an eruption on 19 December 2021. The activity continued and reached a climax around 04:15 UTC on 15 January 2022, and a large eruption generated atmospheric acoustic waves circumnavigating the Earth so large that they could be observed optically via satellite. In addition to all 53 certified IMS infrasound stations registering acoustic signals from this eruption, the hydroacoustic and seismic stations of the IMS recorded the event and its associated phenomena. This event is the largest ever recorded by the infrasound component of the IMS network both in terms of the number of stations and the amplitude of the Lamb wave triggered by the source. The recorded phenomena triggered by the large eruption include a multi-minute duration signal visible at the two hydrophone stations in the Pacific Ocean, HA03 and HA11, originating before the large explosion. The broad-band seismic stations registered the multi-hour ringing of the Earth at 3.7 mHz as was also observed during the Pinatubo eruption in 1991. Finally, atmospheric pressure waves were observed for several days on the infrasound network, and the long duration tsunami was observed at hydroacoustic, near-shore seismic stations in the Pacific and Southern Oceans, as well as at infrasound stations. The presentation will feature analysis of the data from the three IMS waveform technology stations and what can be said about the sequence of events at the source from the IMS data.

The 15 January 2022 Tonga Eruption and Tsunami

Poster Session · Thursday 21 April

Conveners: Peggy Hellweg, University of California, Berkeley; Lori A. Dengler, Humboldt State University; Emile A. Okal, Northwestern University; Seth Moran, U.S. Geological Survey; Stuart Weinstein, PTWC; Summer Ohlendorf, NTWC

Tonga Tsunami Modeling

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On January 15, 2022, the Hunga-Tonga Hunga-Ha'apai volcano, located about 60 km north of Fua'amotu, the main island of Tonga, violently erupted with a powerful explosion, culminating the period of volcanic activity that started in December of 2021. The event generated a strong tsunami that was recorded all over the Pacific Ocean, the waves were also reported in other ocean basins, including the Caribbean and Mediterranean seas. The tsunami size and global reach of the waves have taken the tsunami community by surprise. The more traditional tsunami-generation mechanisms, including caldera formation, landslides and underwater volcano slope failures, struggle to explain the observed tsunami around the world. Multiple mechanisms most probably contributed to the tsunami generation. We present results of ongoing modeling efforts to simulate the 2022 Tonga tsunami employing several generation mechanisms. The instantaneous deformation at the volcano location, shock wave from the explosion and Lamb wave generation mechanisms are considered as tsunami generation mechanisms. Results of multiple modeling simulations compared with the tsunami observations.

World-wide Simulation of Ocean-coupled Air Waves Generated by the 2022 Volcanic Explosion in Tonga

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We use the classic formalism of the Earth's normal modes extended to a model including an atmosphere, with an explosive source located at an altitude of 3.5 km to generate the GR0 branch of airwaves within 0.15-1.6 mHz, as defined by Harkrider and Press [1967]. We focus on the overpressure at the bottom of the atmosphere, which is found to be a robust characteristic of the eigenfunction, essentially independent of the presence of an underlying ocean basin. In turn, at oceanic locations, we use the Dynamic Response Ratio (DRR) to convert it into a vertical displacement of the sea surface. The DRR is found to be strongly dependent on water depth, and marginally on frequency, taking the classic 'hydrostatic' value of (1/rho*g = ~1 cm/mbar) only in the case of a 5-km deep ocean. In shallower basins, the DRR falls rapidly with decreasing water depth, resulting in the disappearance of the maregraphic signal. Our results can be compared with in situ records by ocean-bottom DART sensors, once their reported equivalent amplitudes are corrected for the structure of the ocean-coupled airwave (see companion abstract by Okal [2022]). The records can then be scaled to estimate an equivalent isotropic seismic moment.

Array Studies of the Propagation of Air Waves From the Tonga Explosion at Two European Arrays

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We study the long-distance propagation of air waves, occasionally coupled to oceanic basins, generated by the 2022 Tonga explosion using local arrays of receivers at two European sites. In Ireland, we use 21 atmospheric pressure sensors recording the fundamantal gravito-acoustic mode GR0 [Harkrider and Press, 1964] up to its 4th passage, in the band 0.15-1.5 mHz. Classical beaming defines a vector slowness across the array in general agreement with its value predicted from propagation along the great circle (334 and 154 deg.; 3.15 s/km). In turn, stacked time series compared with normal mode synthetics suggest an isotropic moment of (4 to 10) 10**25 dyn*cm at an altitude of 3.5 km. By contrast, stacking of maregaph records suffers from the non-linear responses of local bays and harbors and from the very shallow seas around Ireland, which minimize the Dynamic Response Ratio. On the other hand, deeper seas around Greek shores lead to well-developed water waves as close as 100 km from the continental mass of Asia Minor (Plymiri, Rhodos), indicating that the coupling to the ocean column takes place well within one wavelength (~180 km) of the coastline. Beaming experiments for a set of 13 Greek tide gauges also yield acceptable results, even though the shape of the array gives poor resolution in absolute slowness, as opposed to a well-resolved azimuth. At both locations, seismic recordings of the airwaves, expectedly stronger on horizontal components, show variable polarizations of particle motions, which can even be transverse to the back-azimuth. This cannot be explained by simple ray theory at the boundary between a solid and a fluid and also violates the generalized response of a horizontal sensor, affected by components of strain and the variation of gravitational potential [Gilbert, 1980]. Similar effects are observed worldwide in environments as different as the Aleutians, the Caribbean and South Pole. Their origin may be rooted in the effect of local topography on the mechanical response of the solid Earth to the passage of the airwave.

An Antipodal Seismic and (Infra)acoustic View on the 15 January 2022 Hunga Tonga-Hunga Ha'apai Eruption from Central Europe

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We report seismic and (infra)acoustic observations of the 15 January 2022 Hunga-Tonga-Hunga-Ha'apai eruption from Switzerland and C-Europe (CHCE) at 153° distance. After clear body-wave phases, complex surface-wave trains arrived between 40-120 min after the main eruption. When they declined, a nearly monochromatic, amplitude-modulated oscillation at 3.7mHz was observed on CHCE broadband stations for more than 14 hours. Spectral and spatio-temporal analyses revealed that this signal represents Earth's fundamental spheroidal normal mode 0S29 with minor contributions from 0S28, 0S37, 0S38. Additionally, we observe a complex pattern of polarity changes passing over the CHCE network that may represent surface waves reflected on crustal heterogeneities. Between 19:30 and 22:30 (UTC), a strongly dispersive wave, corresponding to the minor-arc arrival of the atmospheric, ground-coupled Lamb wave, was recorded on Swiss seismic and infrasound stations. About 5 hours later, we observed the weaker major-arc Lamb wave. 51 hours after the eruption, the second passage of the two Lamb waves branches was recorded. During the passage of the first Lamb wave's high-frequency part, 31 false local-quake detections were triggered by the Swiss network in only one hour when trigger rates of many Swiss stations increased by up to two orders of magnitude. These triggers were caused by high-frequency noise bursts similar to seismo-acoustic signals from sonic booms—several grouping to consistent arrivals traveling over the network on great-circle directions from HTHH. Reliable ear-witness reports of thunder-like sounds from SW-Germany are consistent with the signals' frequency content exceeding 20Hz and may indicate that the eruption was audible in C-Europe at a distance of ~17,000 km. Our observations indicate that the global reach of the HTHH eruption is a consequence of the efficient seismo-acoustic coupling of locally confined and long-reaching atmospheric waves at the observed frequencies.

The 15 January 2022 Event at Hunga Tonga-Hunga Ha'apai, Recorded by Multiparametric Stations in Italy

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The eruption of the volcano Hunga Tonga-Hunga Ha'apai on Jan 15, 2022, 04:14:54 UTC, was such energetic that instruments observed different physical phenomena all over the globe. In Italy, the Istituto Nazionale di Geofisica e Vulcanologia (INGV), who is continuously operating different kinds of monitoring networks, as e.g., the Italian Seismic Network (ISN), micro-barometric and infrasonic stations for monitoring the active volcanoes, ionospheric monitoring network (GNSS and ionosonde), recorded seismic, acoustic and electromagnetic signals originated by this exceptional event. The blast wave generated by the volcanic explosion of Hunga Tunga was recorded by the micro-barometric and infrasound stations installed at Phlegrean Fields (PF), at Stromboli volcano and on Mt. Etna. The first arrival was recorded at ~20:00 UTC, after travelling along the "short" great circle (17600 km), was succeeded by a second onset, about 3:40 h later, arriving at PF from the opposite direction. The mean propagation velocity in both directions was calculated as 310 m/s. The stations of the Etna Radio Observatory (ERO) are also equipped

with micro-barometers, measuring the atmospheric pressure at a sampling rate of 5 min. The first group of atmospheric shock waves was recorded in the evening of Jan 15, 2022, while 36 hours later the ERO-stations observed a second signal after having completed the second orbit. The magnitude of M5.7 of the Hunga Tonga eruption was strong enough to record core phases (PKIKP, PKP), surface reflection of mantle phases (PP, SS), as well as Rayleigh and Love waves, at many stations of the ISN. The atmospheric waves generated by the eruption generated Travelling Ionospheric Disturbances in the ionosphere detected as disturbances in the Total Electron Content calculated by using GNSS data acquired by the GNSS network of INGV and variations of the ionospheric peak layer parameters (foF2, hmF2), recorded by the ionosonde installed on the Italian territory by INGV.

Effects and Observations in Canada of the 15 January 2022 Hunga Tonga-Hunga Ha'apai Eruption

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Following the 15 January 2022 eruption of Hunga Tonga-Hunga Ha'apai, a tsunami watch was issued for the west coast of Canada. Subsequently, small but measureable increases in wave height on the order of 10s of cm were recorded at many locations on the west coast of Vancouver Island and Haida Gwaii. Some Canadians, however, experienced an unexpected effect of the eruption. Residents of several communities in the Yukon, approximately 10000km from the eruption, reported being awakened by loud booms and shaking that lasted for an hour or more. Inspection of data recorded by stations of the Canadian National Seismograph Network in the Yukon found clear signals corresponding to the times and durations of the reported noise. Similar signals were recorded by stations in British Columbia, Alberta and the Northwest Territories. Analysis of these signals indicated that they were consistent with seismo-acoustic signals from the eruption in Tonga. Infrasound waves were recorded by stations in Pinawa, Manitoba and Elginfield, Ontario. The station at Elginfield recorded not only the direct waves but also waves that had traveled in the opposite direction around the Earth. Purely seismic signals were not recorded by stations in Canada but this is perhaps not surprising given the distance from the source and its shallow depth. This presentation will focus on instrumental data and measurements in Canada, presenting a dataset that may be used for more in-depth research in the future.

Observations of the 15 January 2022 Tsunami in Tidal Lagoons of S.E. Australia

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A tsunami warning was announced by the Australian Bureau of Meteorology for the Australian coastline for January 15 and 16. Along the East coast to the South of Sydney, the predicted amplitude was considerably less than the tidal range and there was also a hazardous surf warning in effect for the region. It seemed unlikely that there would be any 'naked eye' observations of the tsunami under those conditions. This coastline is characterised by numerous estuaries with lagoons and swamps that are often open to the ocean only after significant rain. There are many locations where multiple, abandoned river channels are evident as seasonal lakes and disconnected swamps that link during periods of high rainfall. Many of the lagoons lie within the tidal range and may be just a few tens of cm deep so they drain completely and fill over the tidal cycle. The Bega river flows to the ocean at the Mogareeka inlet which has a number of shallow lagoons and swamps that drain completely at low tide. The river flows through a narrow channel and sandbars at the beach which protect the lagoons from the ocean waves. On the morning of January 16, we observed (and recorded) the lagoons periodically filling and emptying over many hours with a period of approximately 20 minutes and with a flow speed considerably higher than the usual tidal velocity. We concluded that we were observing the low-amplitude (~50cm) signal of the tsunami waves that were made visible by the combined effects of very shallow slope and very long flow paths to the lagoon (up to 1km). We were able to correlate our naked-eye observations with tide guage signals in real time and with the nearby river-height guage. While our observations mostly speak to scientific curiosity, the rapid flow speeds that we observed in shallow, tidal lagoons and tidal flats are another reason to be wary of even a small-amplitude tsunami.

California Geological Survey Tsunami Event Response Program: Tonga Tsunami 2022

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The California Geological Survey (CGS) operates a statewide natural hazard event response program that can be activated during and following these events. Activations may include opening the California Earthquake Clearinghouse and/or the deployment of field teams to gather observations of perishable features. Following the eruption of the Hunga Tonga-Hunga Ha'apai volcano in the Kingdom of Tonga, the National Tsunami Warning Center released a Tsunami Advisory for California. Shortly afterwards, the CGS deployed field teams to document the tsunami as it arrived and sent post-tsunami field teams to evaluate the impact of the tsunami. These teams were composed of staff from the CGS, the California Governor's Office of Emergency Services, the U.S. Geological Survey, Cal Poly Humboldt and the University of Southern California. Teams collected physical observations of the tsunami impact using ESRI *Field Maps* and gathered interviews using ESRI *Survey123*. Teams made co-tsunami observations in San Francisco Bay, Half Moon Bay and the Los Angeles/Long Beach harbors. Phase I of the post-tsunami response was prioritized based on the potential for significant impact. Tide gages with the largest tsunami total water elevations were Crescent City 3m, Arena Cove 2.94m, & Port San Luis 2.94m (MLLW), so teams were deployed to these areas including Santa Cruz where damage was reported. For Phase II, teams were deployed to places where we learned more about the tsunami impact during Phase I period: Ventura, Marin, Sonoma, Mendocino, & San Diego counties. Noyo Harbor has no tide gage, so security video footage was combined with a level survey between a U.S. Army Corps of Engineers survey benchmark and a staff plate mounted to the pier to show a maximum water surface elevation of 2.66±0.003m (MLLW). Details about total water levels, observable damage, response protocols and lessons learned will be summarized and posted on the CGS website tsunami.ca.gov/tonga.

Improving Tsunami Event Response and Decision Support Tools in California Based on an Assessment of the Tsunami Generated by the 15 January 2022 Hunga Tonga-Hunga Ha'apai Volcano Eruption

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On 14 January, 2022, at 8:15 pm PST, the Hunga Tonga-Hunga Haʻapai volcanic island erupted generating a trans-Pacific tsunami. At 4:56 am PST on 15 January, two to three hours prior to expected arrival, the National Tsunami Warning Center (NTWC) placed the California coast in a tsunami "Advisory" which forecast tsunami amplitudes between 0.3 to 1.0 meter. The tsunami's arrival coincided with ~1-meter-high tide leading to localized flooding and damage to beaches and harbors. The California Geological Survey (CGS) worked with partners throughout the event to provide information critical to protect people along the coast, including: 1) assisting state and local emergency managers as serving as a subject-matter expert; 2) providing early informational messaging about the tsunami source, expected coincident tides and anticipated tsunami impacts; and 3) collecting information about local impacts and response activities by deploying real-time and post-tsunami observers and questionnaires. Following our post-tsunami assessment, CGS and its partners developed plan to improve future informational products for local emergency managers and harbor officials. We have developed a method to implement our Advisory-level total water-level prediction process, which incorporates tides and other sea-state conditions (i.e., FASTER flood elevation analysis) used to recommend a site-specific local response decision support tool (i.e., "playbooks"), even when there is no information about NTWC forecast amplitudes. In the future, CGS will be in direct communication with harbors that are at an elevated tsunami risk (e.g., Crescent City, Santa Cruz, Ventura), to provide harbor-specific guidance for liveaboards and decision support tools for emergency response. We will continue to work with the NTWC to place a tsunami forecast "breakpoint," or develop an alternative method to separate forecast areas within San Francisco Bay from areas along the outer coast where tsunami hazards are significantly larger.

Tsunami Response and Observations in Santa Cruz, California, USA From the 15 January 2022 Hunga Tonga-Hunga Haʻapai Volcano Eruption

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On 14 January 2022 at 8:15 pm PST, the Hunga Tonga-Hunga Haʻapai volcanic island violently erupted generating a shockwave and tsunami that was recorded on tide gauges along the entire coast of California, with maximum tsunami amplitudes coinciding with daily high tides increasing the potential for flooding. As part of a statewide effort, tsunami impacts to Santa Cruz Harbor were assessed by a team of tsunami scientists and field geologists from the California Geological Survey and the U. S. Geological Survey. This field team was on-site four days after the event to collect maximum tsunami water levels within the harbor area, document observable damage using survey-grade GPS equipment and mobile collection tools and interview harbor officials. Significant tsunami-induced currents were first observed at 7:00 am PST. The largest, tsunami surge peaked at high tide at approximately 8:50 am PST. This led to moderate flooding around the low-lying harbor edges. Wrack lines of detrital material, such as plant and harbor debris, delineated maximum inundation that reached ~4.0-meters above Mean-Lower Low Water and ~2.2-meters above predicted local tidal levels. An initial assessment of $6.5 million in damage to Santa Cruz Harbor was mainly caused by flooding of on-land structures, electrical equipment and harbor infrastructure, such as docks, piles and dredging equipment. In contrast, the Tōhoku-Oki tsunami of 11 March 2011 was a Warning-level event in Santa Cruz, but did not flood on-land because it arrived during low tide, though it caused more damage to the harbor infrastructure due to strong surges. This shows the impact tides can have on tsunami flood potential. Interviews conducted with harbor officials indicated that the 2011 tsunami helped prepare them for emergency response. In addition, harbor infrastructure that was replaced after the 2011 tsunami, helped strengthen the harbor against further damage from the Tonga tsunami.

The 15 January 2022 Tonga Tsunami Advisory on California's North Coast: Notification, Response and Outreach

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At 4:56 AM PST January 15, 2022, the National Tsunami Warning Center (NTWC) issued a Tsunami Advisory for the US West Coast. The alert was the result of the volcanic explosion in the Tonga Islands. Initially considered unlikely to impact the US West Coast, the NTWC issued a statement at 3 AM that the hazard was being reassessed when larger than expected tsunami heights were observed in the Hawaiian Islands. The Advisory triggered a series of conference calls between NTWC, State/County emergency managers to discuss projected arrival times, tsunami heights and likely impacts. Radio, social media and county emergency notification systems were used to notify residents that an Advisory was in place. EAS was not activated because it was not a Warning and the only areas believed at threat were beaches and harbors. A complication of this event was uncertainty in both arrival time and expected peak amplitudes due to the unusual source. The first tsunami surges arrived earlier than the projections based on tsunami propagation times in water, suggesting that atmospheric forcing was likely important. The peak tsunami amplitude in Del Norte and Mendocino Counties was 1.34m and coincided with high tide. There was no significant damage on the North Coast and peak water heights were comparable to those of King Tides. The tsunami provided a test of tsunami communications and highlighted issues of concern: confusion about the difference between Advisory and Warning, and the duration of threat. This was the first time the county emergency notification system had been used for a tsunami. Humboldt County sent out two messages during the course of the event. The event provided an opportunity for outreach and education about the tsunami hazard. Information was posted on social media platforms and led to nearly a hundred-fold increase in visits to the Redwood Coast Tsunami Work Group website. Pages that received the most hits were Tsunami Warnings, FAQs, and Tsunami Hazard Maps. The interest peak waned after three days, underscoring the importance of providing information in near real-time to capture public attention.

Tsunami Velocity and Water Height Measurements of the 2022 Tonga Event Along Northern California and Southern Oregon

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The 15 January 2022 volcanic explosion in the Tonga Islands generated a tsunami in the Pacific Ocean, as well as an atmospheric shockwave observed around the world. The tsunami was expected to arrive in the northern California/southern Oregon coastal region around 1600 UTC. We examined NOAA tide gauge records at six geographic locations in this region (Point Reyes, Arena Cove, Humboldt Bay/North Spit, Crescent City, Port Orford and Charleston) and current profiler data observed at the Humboldt Bay PORTS® site at Chevron Pier. We also developed a proxy data set for currents at another Humboldt PORTS® site, located at Hookton Channel, which had been removed for maintenance during this period. Elevated water levels at tsunami-like periods were clearly observed between 1200 UTC and 1600 UTC at all but the Charleston site, well before the expected tsunami arrival. Maximum tsunami heights (peak-to-trough) during this time range ranged from 0.12 m (North Spit) to 0.44 m (Crescent City). Around 1600 UTC, water levels increased markedly at all six stations, with a subsequent maximum height ranging from 0.41 m (Charleston) to 1.89 m (Crescent City). Dominant periods associated with the tsunami were also location-specific, ranging from 9 min (Arena Cove) to 45 min (North Spit/Humboldt Bay); the dominant period at Crescent City was about 21 min., consistent with previous findings. The tsunami was detectable for a long time at all six stations, ranging from 2.5 d (Charleston) to around 6-7 d (Crescent City and Point Reyes). The water level data support the interpretation that the initial part of the tsunami train was caused by the atmospheric shockwave, which was observed

at the National Weather Service station on Woodley Island (Humboldt Bay), California at approximately 1200 UTC. No clear increase in tsunami currents occurred until around 1600 UTC, after which the maximum peak-to-trough variation was about 78 cm/s at Hookton Channel and 35 cm/s at Chevron Pier.

Hunga-Tonga Games: Unravelling the Timing and Size of the Biggest Volcanic Explosion in 30 Years

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We construct a timeline of The Hunga Tonga – Hunga Haʻapai (HTHH) eruption on 15 January 2022 through analyses of seismic, barometric, infrasonic, lightning and satellite data. Satellite imagery at 0400 UTC showed no ash in the air, but by 0410 UTC, a plume had risen to 18 km. By 0430, the umbrella reached 58 km. USGS determined that an Mw5.8 volcanic earthquake of unknown mechanism had occurred at ~0415 UTC. Gravity waves were observed in satellite imagery and barometric and infrasound stations around the world recorded ultra-low frequency pressure variations of more than 100 Pa, inducing ground-coupled airwaves around the globe and meteotsunamis in the Caribbean Sea and Mediterranean Sea. Tsunami waves were also recorded in coastal areas around the Pacific Ocean. From record sections, we determined speeds of ~3.9 km/s and ~299 m/s for the initial seismic and infrasound signals respectively, converging to an eruption onset time of ~0402 UTC ± 1 minute. The global pressure pulse has a speed of ~314 m/s, consistent with theoretical models for Lamb waves (Bretherton, 1969), suggesting an origin time of ~0415 ± 2 minutes (consistent with the Mw5.8 volcanic earthquake and sharp increases in lightning flash rates) and peaking around ~0429 ± 2 minutes. We suggest that Surtseyan volcanic activity commenced at ~0402, building to a sub-Plinian eruption ~7 minutes later, before a phreato-Plinian eruption commenced at ~0415. The peak Lamb wave amplitude at the closest station (757 km from HTHH) was 780 Pa. Assuming amplitude decay proportional to $1/\sqrt{r}$ (where r is the source-receiver distance), we estimate a lower bound of ~23 kPa for reduced pressure by extrapolation back to 1 km. Adding a near field term that decays as 1/r, we estimate an upper bound of 170 kPa for reduced pressure. Comparison of these values with those from other eruptions (McNutt et al., this session) suggests that the 15 January HTHH eruption was in the VEI 5-6 range.

Source Characterization of the 15 January 2022 Hunga Tonga-Hunga Haʻapai Eruption Using Regional and Teleseismic Waveform Analysis

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Very large volcanic eruptions are rare events for which modern geophysical observations can reveal energy and mass flux between the solid Earth and atmosphere. Only a few events such as the 1980 Mount St. Helens and 1991 Pinatubo eruptions have generated global seismological observations that constrain the space-time force histories from the eruptive process and coupled atmosphere/solid Earth interactions. On January 15, 2022 a series of powerful phreatomagmatic explosions at the Hunga Tonga-Hunga Haʻapai (HTHH) volcano sent an eruptive plume 58 km into the mesosphere, presenting an excellent opportunity to take advantage of extensive modern geophysical observations to study the eruptive process. We examine the source mechanism of the HTHH eruption by analyzing long-period regional surface waves and teleseismic body waves directly excited by the eruption process, as distinct from interactions between atmospheric waves coupled to ground motions. The source process is likely associated with pressure drop in the magmatic conduit along with reaction forces to the ejection jet. The latter process is more seismogenic than the related implosive process, so we assume a surface point-force with varying orientations to deconvolve and model the seismic wavefield for periods less than 100 s, dominated by packets of body wave and surface wave arrivals. A simulated annealing non-linear inversion for a vertical source provides a complex force time history, F(t), which is in good agreement with estimates of F(t) from deconvolutions of stacked body waves and stacks of surface wave deconvolutions. The observations are well-explained by a single force reaction to the explosion sequence. The main eruptive process lasted ~1.4 hrs and was composed of multiple pulses (explosions) that reduced in amplitude over time, with a secondary eruption ~4.2 hrs later. The peak magnitude of the vertical force is ~ 9×10^{12} N. Estimates of energy and mass flux through the process will be presented.

Seismoacoustic Yield Estimation of the January 2022 Hunga-Tonga Eruption

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Seismic observations of explosions provide crucial data on the yield of underground explosions which cannot easily be estimated from other geophysical methods. Here we compare and analyze the seismic yield estimates obtained using various body- and surface-wave magnitudes and empirical magnitude-yield relationships which have been calibrated using known explosion yields, which may or may not be applicable to the Tonga region or eruption source. These magnitude-yields are compared with moment tensor solutions and yield estimates obtained from infrasound to constrain the energy partitioning of the explosion. We focus on analyzing the coupling and transfer of energy into the crust, water column and atmosphere. We also explore any constraints on the presence of possible secondary sources (e.g., submarine landslides). To facilitate this analysis, we locate and determine the magnitudes of nearby earthquakes that occur before and after the eruption. Using these earthquakes, we compute spectral ratios of waveform envelopes of body-wave coda that remove path and site effects to reveal precise, relative source moment. In addition to providing unprecedented constraints on the mechanics of submarine eruptions, analysis of this event allows us an opportunity to compare and evaluate current yield estimates using canonical and novel monitoring methods in an uncalibrated area.

50-State Update of the USGS National Seismic Hazard Models

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Edward H. Field, U.S. Geological Survey (field@usgs.gov); Morgan P. Moschetti, U.S. Geological Survey (mmoschetti@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Kishor S. Jaiswal, U.S. Geological Survey (kjaiswal@usgs.gov); Sanaz Rezaeian, U.S. Geological Survey (srezaeian@usgs.gov); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov); Emel Seyhan, Risk Management Solutions, Inc. (emel.seyhan@rms.com)

2023 US 50-State National Seismic Hazard Model

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We are developing the 2023 U.S. National Seismic Hazard Model for all 50 states by applying new seismicity, fault rupture models and ground motion assessments. We consider two types of models: (1) a public model that guides hazard assessments intended for building code provisions and policy applications and (2) a research model geared towards less formal applications that may be included in future public models. New data and methods will be introduced in the 2023 earthquake source components: earthquake catalogs—excluding induced earthquakes, alternative declustering methods, spatially smoothed seismicity, scaled rates to account for aftershocks, new geodetic and geologic data and fault rupture models accounting for a more complete representation of potential earthquakes in Alaska, Hawaii and the conterminous U.S. Improved ground motion models (GMMs) consider new NGA-Subduction, modified NGA-East and NGA-West2, as well as other published models. Some NGA-subduction and earthquake source models contain changes in median and aleatory variability that need to be evaluated and weighted. Basin amplification models will also consider 3D simulations with potential modifications at basin edges. Preliminary assessments indicate several relatively shallow Intermountain-West basins exhibit greater long-period amplifications than estimated by NGA-West2, potentially warranting additional basin-specific observations and simulations. New stress drop, tomographic and other geophysical models help refine the complex boundary between the tectonically stable and active regions used in assigning GMMs. The research model may incorporate more geological information on timing of past earthquakes for a time-dependent assessment and regional variations in earthquake shaking accounting for a partially non-ergodic ground motion representation. Scenarios and population exposure assessments of these models will help users assess impacts of the earthquakes.

The 2023 Update of the Alaska National Seismic Hazard Model

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The U.S. Geological Survey (USGS) is developing a 50-state update to the National Seismic Hazard Model (NSHM). For Alaska, we are considering updates to both the source, or earthquake rupture forecast (ERF), and ground motion model (GMM) components. The ERF will include updates to the crustal fault inventory, currently available as a data release, and consider geologic and geodetic rate models. For the large-magnitude subduction interface model, we consider a segmentation and recurrence model being developed by the USGS and partners participating in the National Tsunami Hazards Mitigation Project (NTHMP). A new catalog that includes earthquakes from 2007 to present has been developed to inform the rate model for the both the crustal and subduction gridded seismicity components. Calculation of the gridded seismicity rate model considers additional declustering and smoothing techniques. We also use the SLAB2 subduction geometry model to constrain the interface and slab geometry. In addition, SLAB2 codes are used to segregate the statewide Alaska catalog into active crust, subduction intraslab and subduction interface event catalogs, which are necessary for developing independent rate models for each tectonic setting. For the GMM component, we are evaluating the new NGA-Subduction GMMs with regionalization for Alaska for both interface and intraslab settings and the NGA-West2 GMMs for the active crust. Here we present a preliminary implementation of the above model components and comparisons to the prior NSHM from 2007.

Sensitivity Testing the 2023 Update of the National Seismic Hazard Model

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The U.S. Geological Survey's upcoming 50-state update to the National Seismic Hazard Model (NSHM) will consider a wide range of new data related to seismic source, i.e., the earthquake rupture forecast and ground motion model components. Robust sensitivity testing is important to ensure correct implementation and to evaluate the relative impacts of proposed changes to the model. Comprehensive testing of earthquake hazard is difficult due to the dimensions of a hazard result, which considers multiple site conditions and intensity measurement types. We present a workflow to efficiently compute ground motion difference and ratio maps for selected probabilities of exceedance and evaluate NSHM sensitivity. Coupled with uncertainty analysis supported in the updated nshmp-haz probabilistic seismic hazard code base, we can begin to evaluate logic tree branches for the NSHM update. This will allow us to determine which branches have the greatest impact on hazard and potentially prune NSHM logic trees, thereby focusing future development efforts. As examples, we present differences in hazard arising from the use of the new NGA-Subduction ground motion models along the Cascadia subduction zone and the Aleutian arc, as well as new fault and zone sources in the central and eastern U.S.

Earthquake Scenario Development in the 2023 USGS National Seismic Hazard Model Update

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Earthquake scenarios have been shown to be an effective tool to convey potential impacts to a community in a shaking event. Furthermore, these scenarios can be used to communicate the underlying seismic hazard and risk to audiences who are not well versed in interpreting the results from probabilistic seismic hazard assessment (PSHA). To address these points, a suite of earthquake scenarios is being developed by the U.S. Geological Survey (USGS) to accompany the release of the 2023 update to the National Seismic Hazard Model (NSHM). This presentation describes the motivation, structure and preliminary results of this work to seek participation and guidance from relevant stakeholders. As such, plans for the formulation of a working group to oversee the project direction and scenario development are also described. The scenario locations include urban centers such as Honolulu, Reno, Las Vegas, Seattle, Salt Lake City and New York City. Scenario selection can be based on known seismic sources or the disaggregation based on probabilistic hazard, both of which are considered as a part of the NSHM. The NSHM source and ground motion models are also used in the scenario development. Impact products include estimates from USGS ShakeMap (modified to be consistent with NSHM), PAGER and Ground Failure as well as additional urban loss assessments using the OpenQuake Engine and Hazus. As a part of this paper, we show and example of our process for Honolulu. The 2021 Hawaii hazard model indicates that, in Honolulu, for the 2475-yr ground motion and a time-averaged shear-wave velocity in the upper 30m (Vs30) of 760 m/s, the spectral acceleration at 0.2 s and 1.0 s periods are approximately 0.6 g and 0.15 g, respectively. This hazard mainly originates from shallow and deep non-summit gridded seismicity in the region. Accordingly, we considered a scenario which is a repeat of the 1871 M7.5 Lanai earthquake occurring in the Molokai Fracture Zone. Preliminary results showed estimated intensities of MMI 6–7 in Honolulu and the potential for 1 to 10 fatalities in the region.

An Argument for Time-dependent National Seismic Hazard Maps

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The U.S. Geological Survey National Seismic Hazard Maps depict time-independent seismic hazard. Hence current seismic design practice as reflected in the resulting International Building Code is based on time-independent probabilistic seismic hazard analyses. We argue that the National Seismic Hazard Maps should consider time-dependent hazard when paleoseismic records are sufficient to account for the elapsed times on faults. This is particularly criti-

cal if the elapsed times exceed the mean recurrence intervals suggesting that a large earthquake may be eminent. However, even when such fault recurrence information is not available, we believe some form of time-dependent hazard should be considered in the National Seismic Hazard Maps considering non-Poissonian recurrence (e.g., Biasi and Thompson, 2018). The key to an accurate time-dependent seismic hazard assessment for a fault is information on its mean recurrence interval, elapsed time since the most recent earthquake, and their uncertainties. Although such information is generally unavailable for most faults in the U.S., it is available for some of the most hazardous regions in the U.S. including along the San Andreas fault system, the Wasatch fault zone, the Cascadia subduction zone, and the New Madrid and Charleston seismic zones. We illustrate the time-dependent hazard using the forecast model of the Working Group on Utah Earthquake Probabilities for the Wasatch Front. The seismic hazard in this region is generally dominated by the five central segments of the 350-km- long Wasatch fault zone, which has ruptured repeatedly in M 6.8 and larger earthquakes. We illustrate the differences in time-independent and time-dependent hazard for three cities along the Wasatch Front where the mean recurrence intervals equal, exceed, or are a fraction of the elapsed time since the last large earthquake and compare these results with the National Seismic Hazard Maps.

Overview of Earthquake Rupture Forecasts for the 2023 USGS NSHM Update

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On behalf of a very large working group, this presentation provides a summary of anticipated improvements for the time-independent Earthquake Rupture Forecasts (also known as seismic source characterizations) for the 2023 update of the USGS National Seismic Hazard Model. The main goals are a more uniform application of methodologies across the country, a more complete representation of epistemic uncertainties and establishing a basis for an eventual operational earthquake forecasting capability nationwide. Efforts also include a better representation of multi-fault ruptures and the ability to apply variable degrees of segmentation throughout each fault system (e.g., a wider range of models than applied previously in California). The presentation also summarizes updated geologic constraints, deformation models, statistical seismology components, efforts to operationalize various computer codes, hazard and risk sensitivity analyses (e.g., for logic tree refinement) and any loose ends that continue to pose a challenge.

Lower Seismogenic Depth Model of the Western US Based on Seismicity

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We present a model of the lower seismogenic depth of the western U.S. estimated using the hypocentral depths of event M>1 from the USGS National Earthquake Information Center (NEIC) catalog from 1990 to 2021. Previous determination of the seismogenic depth for the UCERF3 model was based on work by Petersen et al. (1996) who used seismicity cross sections along major fault zones in California. Our study uses the most up-to-date seismicity depth distribution provided by the USGS NEIC comprehensive catalog. We substituted the seismicity in southern California with the relocated catalog of Hauksson et al. (2021), which provides higher precision hypocentral locations. We calculated the average depth of the deepest 10% of the merged catalog using an adaptive radius of 50 km or more depending on the density of the seismicity distribution. This distance is about 50 km in California, but could extend to 150 km in the western US outside of California where seismicity is sparser. Along the San Andreas Fault, the deepest seismogenic depth is located around the Big Bend segment at about 27 km, whereas the shallowest depth is located along the Rogers Creek and Macaama Fault segments at about 8 km. For the western U.S. outside California, the depth varies between 10 to 20 km with an average around 14 km. This new seismogenic depth distribution correlates closely with the heat flow distribution for the western U.S. region (Blackwell et al., 2011) and the lower crust low shear velocity distribution (Shen and Ritzwoller, 2016). We have also found very good agreement between the seismogeneic depth and the large earthquake rupture depths derived from coseismic slip distributions in the region. This updated seismogeneic depth model could be used to recalibrate the lower seismogenic depths assigned to the geologic faults in the western U.S. and be applied to the background seismicity source model in the 2023 update of the National Seismic Hazard Model.

Early Results From Deformation Models of the Western US for the 2023 Update to the US National Seismic Hazard Model

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We describe geodetic and geologic information assembled for the 2023 update to the National Seismic Hazard Model (NSHM), a set of deformation models to interpret these data and implications for earthquake rates in the Western US. Recent updates provide much larger datasets of GNSS crustal velocities than used in the 2014 NSHM, as well as hundreds of new faults considered as active sources for the current NSHM. These data are interpreted by four quantitative models of deformation which estimate fault slip rates and their uncertainties together with off-fault moment release rates. Key innovations in the current NSHM relative to past practice include: (1) the addition of two new (in addition to two existing) deformation models, (2) the inclusion of hundreds of additional (primarily very low slip rate) faults and the availability of more constraints on geologic slip rates, (3) accounting for fault creep through development of an independent creep-rate model whose results are incorporated into the deformation models and (4) accounting for time-dependent earthquake-cycle effects through development of viscoelastic models of the earthquake cycle along the San Andreas fault and the Cascadia subduction zone. The current deformation models provide a new assessment of discrepancies between geologic and geodetic slip rates, while at the same time highlighting the need for both geologic and geodetic slip rates to robustly inform the earthquake rate model.

Proposed Updates to the UCERF3 Fault System Inversion Approach for Use in the 2023 Western US ERF

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The 3rd Uniform California Earthquake Rupture Forecast (UCERF3) utilized an inversion-based methodology that solves for the rates of supra-seismogenic on-fault earthquakes in a complex, interconnected fault system. Based on recent improvements aimed at simplification and sampling a wider range of epistemic uncertainties, this approach is proposed to be expanded to fault systems throughout the Western U.S., including Alaska, for the 50-state update to the 2023 National Seismic Hazard Model. We will highlight these improvements using UCERF3 data as input, and compare the proposed model to published UCERF3. We will also describe a suite of tools available to the user community for running inversions and interrogating inversion solutions.

Model improvements under consideration include: a new and more physically-consistent multi-fault rupture plausibility model; a variable segmentation constraint to dial the propensity of multi-fault ruptures up and down; a decoupling from the gridded seismicity model; a simpler methodology for determining the regional target magnitude frequency distribution (MFD); a wider range of fault section MFD nucleation constraint options; better constraint weighting to more evenly fit all available data relative to their uncertainties and several improvements to the simulated annealing algorithm. In aggregate, these changes lead to a suite of models that better fit the available data constraints, encompass a broader range of uncertainties, and are more computationally efficient than UCERF3.

Paleoseismological Perspectives on Megathrust Locking, Rupture and Tsunami Hazard in Alaska

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We review findings from over a decade of paleoseismological studies that apply to 5 sections of the Alaska-Aleutian subduction zone (addressed from west to east) in the 2023 USGS Alaska seismic hazard map update. (1) In the Fox Islands, large tsunamis occur every 270–340 yrs. The most recent tsunami, launched by the M8.6 1957 Andreanof Islands rupture, stranded drift logs 18–23 m above sea level. The distribution of tsunami deposits indicates that the 1957 rupture extended into a presently creeping part of the megathrust. Tsunami models require near-trench rupture in 1957 to generate waves consistent with tide gage records and tsunami deposits. (2) At Sanak Island, 5 sand sheets record large tsunamis in the past ~4200 yrs; the most recent tsunami was generated by the 1946, M8.6 Unimak Island earthquake. We present new constraints on coseismic vertical displacement in the 1946 earthquake based on geodetic surveys in 1937, repeat bathymetric datasets, and modern tidal observations. Sanak Island lacks evidence for a 1788 tsunami implied by Russian documents. (3) On three Shumagin Islands we found evidence for late Holocene coastal stability, inconsistent with large coseismic slip. Past storms or tsunamis flooded below the highest tides based on coastal stratigraphy. Persistent late Holocene megathrust creep probably accompanied M7–8 seismicity in the region of the 2020 M7.8 Simeonof Island earthquake. (4) In the Semidi Islands, geodesy indicates that the megathrust is firmly locked and coastal geology records local tsunamis every 180–270 yrs, including events in 1788 and 1938. (5) The Kodiak section ruptures on average every 300–350 yrs—roughly half the ~650 yr interval for the adjacent Prince William Sound section. Work on Sitkinak Island implies that the 1788 rupture crossed the western boundary of the 1964 rupture. Our observations suggest that (a) megathrust coupling evolves through space and time; (b) the 1957 tsunami involved near trench rupture; (c) large tsunamigenic earthquakes occur more often than in the current seismic hazard map and (d) rupture boundaries vary from one earthquake cycle to the next.

Updates to the Ground-motion Characterization for the 2023 US National Seismic Hazard Model

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The ground-motion characterization for probabilistic seismic hazard analysis requires detailing the distribution of earthquake ground motions for all seismic sources, including their medians, aleatory variabilities and epistemic uncertainties. We summarize progress towards the ground-motion updates for the 2023 U.S. National Seismic Hazard Model (NSHM) which includes (1) evaluation of models for basin amplification and the amplification effects of deep sediments, (2) introduction of long-period (T>1 s) basin effects from 3D simulations in southern California and the Cascadia subduction zone, (3) implementation of new subduction-zone (NGA-Subduction) ground-motion models (GMMs), (4) updated treatment of the boundary between the western U.S. and the central and eastern U.S. and (5) consideration of seismic directivity models. Incorporation of additional sedimentary basins and deep-sediment effects are motivated by the expansion of the U.S. NSHM to long-period ground motions, which show significant effects not captured by shallow site response (i.e., Vs30) models. Using new ground motion data, we evaluate basin effects in the Reno, NV region and California Central Valley and in the Atlantic and Gulf Coastal Plains, where we have recently compiled sediment thicknesses. We develop basin-amplification models from 3D simulations in southern California using a partially nonergodic approach and in the Seattle basin using a method consistent with current tall-building design guidelines. The NGA-Subduction GMMs represent improved treatment of regional effects and epistemic uncertainty, and we plan NSHM implementation via a logic-tree approach. Our initial implementation of existing seismic directivity models focuses on spatially adjusting the median ground motion with a corresponding adjustment in aleatory variability. The proposed changes to ground-motion characterization and the sensitivity of seismic hazard to the new models will be presented and discussed at public workshops in 2022 prior to final implementation in the NSHM.

Assessment of Western US Basin Response and Implementation in the 2023 Update of the US National Seismic Hazard Model

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The U.S. Geological Survey will update the 50-State National Seismic Hazard Model (NSHM) in 2023, which will include an expanded assessment of sedimentary basin response in the western U.S. Basin effects broadly encompass amplification of long-period ($T > 1$ s) ground motions due to deep sediments, azimuthal dependence for elongated sediment-filled structures (waveguides) and basin-edge effects including focusing. We target Reno and Las Vegas (Nevada), Portland and Tualatin (Oregon) and the California Central Valley as new focus areas for incorporating basin effects into the NSHM. We compare recently processed ground-motion datasets across Nevada to predicted motions from NGA-West2 ground-motion models (GMMs) to assess GMM performance using new maps of depths to shear-wave (V_S) isosurfaces ($Z_{1.0}$ and $Z_{2.5}$: depth to V_S = 1.0 and 2.5 km/s, respectively). We perform a similar analysis for the Central Valley using new $Z_{1.0}$ and $Z_{2.5}$ surfaces created from existing seismic velocity models. We also revisit basins included in the previous (2018) NSHM update using new data or models for improved assessment. We evaluate the treatment of basin effects in Seattle using the newly published NGA-Subduction GMMs, testing an alternative $Z_{2.5}$-based model of basin amplification that is independent of the time-averaged V_S to 30 m depth (V_{S30}). For southern California basins we consider new studies that differentiate between basin and basin-edge sites. We are evaluating whether special treatment of basin-edge sites within the NSHM is warranted, and if so, which basins amplify or deamplify ground motions relative to the default values predicted by the GMMs. In the previous NSHM update, such deamplification was not included in the shallow portion of basins because of an inconsistency with observations at basin edges. We also leverage 3D simulations to develop basin-amplification models both in southern California and in the Seattle basin. This broad effort will provide a framework to assess basin response in areas with varied ground-motion and geophysical data in seismically active regions around the U.S. and worldwide.

Probabilistic Seismic Hazard Analysis in Seattle Using Non-ergodic GMMs Based on 3D Simulation Results for Cascadia Interface Earthquakes

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Significant path effects on the ground motions in Cascadia can be seen in the suite of numerical simulations of ground motions from megathrust earthquakes on the Cascadia subduction zone through a 3-D crustal structure developed by the M9 project (Frankel et al., 2018). Using these simulation data, the Abrahamson and Gulerce (2020) ground-motion model (AG20) is modified to capture the 3-D path effects from the M9 simulations. The basin-depth (Z2.5) scaling in the AG20 GMM is modified to be consistent with the average scaling from the 3-D simulations. The varying coefficient model is used to estimate the spatial distribution of the non-ergodic site terms for the region covered by the 3-D velocity model for the long-period range (1 - 10 sec). By including the non-ergodic site terms, the aleatory variability for the 3-D simulations is reduced by 15-25% compared to an ergodic standard deviation. The epistemic uncertainty in the non-ergodic site terms for a single 3-D velocity model is small due to 30 realizations of the source, but there should be uncertainty due to alternative 3-D models. Without simulation results for different 3-D velocity models, we assumed that the epistemic uncertainty is one half of the between-site standard deviation from the simulations.

The application of non-ergodic GMMs in the probabilistic seismic hazard analysis (PSHA) requires three modifications to the ergodic GMMs: (1) reduce the aleatory standard deviation of the ergodic GMM, (2) estimate the source/site-specific non-ergodic terms and (3) estimate the epistemic uncertainty of non-ergodic terms. For example sites in the Seattle region, use of the non-ergodic GMM leads to significant changes in the 3-sec hazard for specific sites. The changes in the hazard from interface events only lead to increases of up to a factor of 1.5 and decreases of up to a factor of 2.5 in the 2500-yr ground motion for the Cascadia source by itself. The change in the total hazard is less (up to a factor of 1.25 increase of decrease) because no change is made to the hazard from crustal or slab events.

A Ground-motion Prediction Model for Induced Earthquakes for Central and Eastern United States

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We developed a new ground motion model (GMM) for predicting ground shaking of future induced earthquake events in Central and Eastern United States. The new model is a new empirical-hybrid ground motion model (GMM) for small-to-moderate potentially induced earthquakes for Central and Eastern United States (CEUS). For this study, Pezeshk et al.'s (2018) model was used as the base model which was developed and calibrated for tectonic events in Central and Eastern North America (CENA) as part of the Next-Generation Attenuation-East (NGA-East) project. The model is a calibrated version of the base model by using a comprehensive database of potentially induced ground motions with a smaller range of magnitudes and depths than tectonic earthquakes. We implement a compiled dataset containing more than 31,000 strong-motion records from 2,596 earthquake events recorded at 370 stations. The Gulf Coast region's all earthquake events and stations are excluded from the database of this study.

The functional form of the developed model includes 5 coefficients are extracted by using a mixed-effect regression algorithm. The proposed GMM is derived for the peak ground acceleration and response-spectral ordinates at periods ranging from 0.01 to 10.0 sec, magnitudes ranging from 3.0 to 5.8 and hypocentral distances up to 200 km. The proposed GMM has applicability in long-term and short-term U.S. Geological Survey National Seismic Hazard Maps and for the hazard evaluation of induced seismicity. We also assessed the performance and predictive capability of the developed GMM through a set of comprehensive residual analyses and compared the proposed GMM with five recently developed GMMs for earthquakes in CENA. The GMMs are utilized in the PSHA assessment of induced earthquakes through the observed data for CEUS.

Exploring Potential Implications to Engineering and Risk Applications From Including Epistemic Uncertainties in Hazard for the USGS 2023 NSHM

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The U.S. Geological Survey (USGS) National Seismic Hazard Model (NSHM) is a flagship product that provides probabilistic estimates of seismic hazard for the United States. Example outputs include annual frequencies of exceeding ground motion thresholds and maps of ground motions corresponding to specified return periods (i.e., probabilistic ground motions). Since 1976, the USGS has periodically updated the NSHM to incorporate the latest available science and data, which improve estimates of ground motions over time. To enhance the usefulness of the NSHM, the forthcoming 2023 update will better represent epistemic uncertainties in estimation of seismic hazard.

To better understand the potential implications of including estimates of uncertainty in the hazard, we focus on three typical engineering and risk applications, namely, determining (i) probabilistic ground motions from hazard curves for developing design criteria, (ii) earthquake scenarios from hazard disaggregation and (iii) seismic risk to critical infrastructure systems. First, we adopt a recently developed model for approximating epistemic uncertainty in hazard as a placeholder for the upcoming 2023 update because the actual uncertainties are not yet available. Then, we use the approximate uncertainties to examine (i) how much probabilistic ground motions have changed across NSHM updates, (ii) how the disaggregation output varies with different input fractiles of hazard and (iii) how influential is seismic hazard relative to other inputs in a seismic risk assessment of gas transmission pipelines. To explore potential geospatial dependencies, we consider three locations in the conterminous United States: (i) Los Angeles, California, (ii) Seattle, Washington and (iii) Memphis, Tennessee. Although not comprehensive, documenting these example applications would help end users of the NSHM better understand potential implications of including epistemic uncertainties in hazard for the forthcoming 2023 update.

50-State Update of the USGS National Seismic Hazard Models

Poster Session · Wednesday 20 April · Conveners: Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Edward H. Field, U.S. Geological Survey (field@usgs.gov); Morgan P. Moschetti, U.S. Geological Survey (mmoschetti@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Kishor S. Jaiswal, U.S. Geological Survey (kjaiswal@usgs.gov); Sanaz Rezaeian, U.S. Geological Survey (srezaeian@usgs.gov); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov); Emel Seyhan, Risk Management Solutions, Inc. (emel.seyhan@rms.com)

A New Alaska-Aleutian Subduction Zone Rupture Model for Use in the National Seismic Hazard Model

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The Alaska portion of the USGS National Seismic Hazard Model will be updated by 2024. Here we report progress on a new rupture model for the Alaska-Aleutian subduction zone, leveraging a parallel effort by a USGS Powell Center working group on tsunami sources for the National Tsunami Hazard Mitigation Program.

We define fault sections based on geodetic coupling, prehistoric earthquake and tsunami recurrence, historic ruptures and geologic structure. From east to west along the subduction zone, several key findings guide construction of the new rupture model. In the 1964 Mw 9.2 rupture area, recurrence rates for presumed great (Mw 8+) events vary from ~600 years (Prince William Sound section) to ~300 years (Kodiak section), and geologic evidence suggests rupture of multiple patches varies in space and time. Westward along the Semidi section, recurrence rates of large, tsunamigenic ruptures are far more frequent (~210 years) than previously assumed based on new geologic and geodetic data and the 2021 Mw 8.2 Chignik earthquake. The last >Mw 8.5 rupture along the Semidi section appears to have occurred in 1788. Long-term behavior of the poorly coupled Shumagin section remains enigmatic despite two large (Mw 7.6 and 7.8) ruptures in 2020, and the neighboring Sanak section, also relatively poorly coupled, appears to produce large events every ~2000 years, most recently in 1946 (M8.6). Prehistoric tsunami data suggest that the recurrence of large ruptures in the Fox Islands is ~210 years. Paleoseismic data doesn't exist west of the Fox Islands, so rupture rates along the western 1900 km of the megathrust to Komandorski rely on geodetic constraints. Coupling models suggest that recurrence rates are shorter than previously assumed from seismicity. Many issues require more work, including the recurrence of shallowest interface ('tsunami earthquakes') and intraslab events, the persistence of rupture patches and how to best develop time-dependent calculations given the rupture areas of historic and prehistoric earthquakes are poorly constrained.

Determination of Seismological Parameters in Central and Eastern North America

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The main objective of this study is to determine seismological parameters in Central and Eastern North America (CENA), including constraints on the geometrical spreading, anelastic attenuation, stress parameters and site attenuation parameters (kappa). We used the recently developed and published Ground Motion Models (GMMs) for the NGA-East to determine the seismological parameters.

We used a genetic algorithm (GA) to invert weighted geometric mean estimates of horizontal response-spectral acceleration from the empirical NGA-East ground-motion models to successfully estimate a consistent set of seismological parameters that can be used along with an equivalent point-source stochastic model to mimic the general scaling characteristics of these ground-motion models. The inversion is performed for events of M 4 – 8.0, R_{RUP} = 1 to 300 km, T = 0.01 – 10 sec (f = 0.1 – 10 Hz).

This study is the first to perform a formal inversion using the extensive and peer-reviewed CENA GMMs developed for the NGA-East project and using a formal GA approach. The approach has been validated by using simulated small-to-moderate magnitude and large-magnitude data derived from the NGA-West2 GMMs (Zandieh *et al.*, 2016, 2018; Pezeshk *et al.*, 2015).

Hybrid Empirical Ground-motion Models With Simulation-based Site Amplification Factors for the Island of Hawaii

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The primary purpose of this study is to develop Ground Motion Models (GMMs) with Site Amplification Factors for the island of Hawaii. We develop GMMs using the Hybrid Empirical Method (HEM) with a companion simulation-based Site Amplification Model for the V_{S30} requirements of the National Seismic Hazard Mapping program (VS30 is time-averaged shear wave velocity in the upper 30 m of the site). Stochastically simulated Ground Motion Intensity Measures (GMIMs) in the host and target regions are utilized in HEM to develop adjustment factors that are applied to empirical GMIM predictions in the host region. The island of Hawaii, the target region in this study, has been the site of numerous large earthquakes with a growing database of strong ground motion observations. The crustal earthquakes on the island of Hawaii originate from volcanic activity and include both swarms of small-magnitude volcanic events and larger tectonic events. Ground motion modeling on the island of Hawaii is challenging due to the depth distribution of events and different anelastic attenuation characteristics. In the absence of an amplification model for the island of Hawaii, the proposed simulation-based amplification model can be used not only for the proposed GMMs but for all other previously developed GMMs that will be considered in the upcoming national seismic hazard maps updates.

Since the hazard comes both from shallow crustal earthquakes and from deep events for the island of Hawaii, two separate GMMs are being developed. We consider the focal depth of 20 km to distinguish between shallow crustal and deep earthquakes. A moment magnitude range of 4.0 to 7.5 and Joyner-Boore distances of up to 400 km are considered. For the required seismological parameters in WNA, we use Zandieh et al. (2018) results. For the required seismological parameters in the island of Hawaii, we use Wong et al. (2020).

Investigating the Effects of Declustering Choices on Probabilistic Seismic Hazard Assessments

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The U.S. Geological Survey (USGS) probabilistic seismic hazard assessments have relied on spatially smoothing and declustering (i.e., removing aftershocks from) an earthquake catalog in order to produce an estimate of independent (background) seismicity rates. Past versions of the USGS National Seismic Hazard Model (NSHM) primarily used the Gardner and Knopoff (1974; hereafter GK74) method. However, the development of the 1-year seismic hazard forecasts for the central and eastern U.S. revealed issues with the use of GK74, which did not seem to work well in regions of induced seismicity (Petersen et al., 2018). It also did not perform well in the recent update of the Hawai'i NSHM, perhaps because the space-time windows used to identify aftershocks were unsuitable for seismicity influenced by time-varying volcanic processes (Petersen et al., 2021). Moreover, because aftershocks are not physically distinguishable from mainshocks, declustering is a non-unique process, and there are many different methods available that produce different declusterings of the same catalog.

As the USGS conducts a 50-state update of the NSHM for 2023, we examine the sensitivity of the hazard models to declustering. We are primarily interested in the differences of the spatial probability density function of earthquakes following declustering and changes in the b-value. Differences in these characteristics can lead to differences in the forecasted rate of larger earthquakes. The methods that we compare include GK74, Reasenberg (1985), the nearest-neighbor declustering method of Zaliapin et al. (2008), and the ROBERE method of Llenos and Michael (2020). Preliminary results suggest that different declustering methods can result in different smoothed seismicity rate models and different b-values, which constitute a source of epistemic uncertainty that should be included in the final hazard model.

Investigation and Re-calculation of TL: The Long-period Transition Parameter

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In recent years, many changes have been made to the design response spectrum used in ASCE 7, most notably the 22-period response spectrum implemented in 2020 NEHRP Recommended Provisions and ASCE 7-22 (Kircher, 2019). One item that has not been investigated or re-visited since its first appearance in FEMA 450-1/2003 is the long-period transition period parameter, T_L. The long-period transition period parameter was introduced and defined as the corner period that marks the transition from the constant velocity to the constant displacement segments of the response spectrum. The long-period transition period parameter is primarily important for long period structures such as high-rise buildings and bridges.

The most current estimation of T_L used in engineering design standards is loosely based on a correlation between moment magnitude Mw and T_L that does not account for stress drop $\Delta\sigma$ or the source velocity β (ASCE, 2016). This project aims to include both $\Delta\sigma$ and β in its estimation of T_L. First, inversion of ground-motion models for Central and Eastern United States (CEUS) is used to determine $\Delta\sigma$ for CEUS, and we will use the published information for $\Delta\sigma$ for Western United States (WUS). Then the exact definition of the corner period will be used to estimate T_L. The result will be updated national maps of both $\Delta\sigma$ and T_L.

Model Selection and Epistemic Uncertainty Quantification of the Ground Motion Models for Induced Seismicity in Central East North America

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Induced seismicity refers to earthquakes related to human activity and is known as small-to-moderate magnitude size earthquakes. In the last decade, the rate of induced seismicity has increased dramatically in Central and Eastern North America (CENA) due to the mining and hydrocarbon industrial activities such as wastewater injection operations, hydrocarbon extraction, hydraulic fracturing for shale gas exploitation, hydrocarbon storage operations, CO2 geological sequestration and hydraulic stimulation of geothermal fields. To this end, induced earthquake hazard has become an important topic and probabilistic seismic hazard analysis (PSHA) can be used to assess such hazard for a region. In the current practice of PSHA, the different estimates of ground motions predicted by ground-motion models (GMMs) are attributed to epistemic uncertainty. To have a reliable PSHA, such epistemic uncertainty should be quantified and addressed appropriately. In this study, we quantify the epistemic uncertainty associated with the induced GMMs that are proposed or developed for CENA. For this purpose, we use a catalog of induced earthquake ground motions from 28 events with 4.0 at distances up 75 km with focal depth up to 10 km from 2011 to 2018. Moreover, we consider candidate GMMs that are developed based on small-to-moderate size induced, potentially induced ground-motion events of CENA and NGA-West2. We apply a data-driven selection method based on the deviance information criterion to rank the candidate GMMs and select the best GMM as the backbone model. Then, we quantify a scale factor that is representative of the epistemic uncertainty associated with the induced GMMs. The scale factor is then added and subtracted from the backbone GMM to cover the spread in the predictions from other GMMs and the recorded ground motions. The results of this study will improve our confidence in the induced PSHA results for CENA.

Revised Earthquake Geology Inputs for the Central and Eastern United States and Southeast Canada for the 2023 National Seismic Hazard Model Update

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It has been nearly a decade since updates to seismic sources in central and eastern North America (CENA) were last assessed for the 2012 Central and Eastern United States Seismic Source Characterization for nuclear facilities (CEUS-SSCn) and 2014 United States Geological Survey National Seismic Hazard Model (NSHM) for the conterminous U.S. In advance of the 2023 NSHM update, we created 3 databases to summarize and characterize new fault source information for CENA. These include a fault section, fault zone polygon and earthquake geology (fault slip rate, earthquake recurrence intervals) database, which document updates to fault parameters used in prior seismic hazard models in this region. The 2012 CEUS-SSCn and 2014 NSHM fault models served as a foundation, as we revised and added fault sources where new published studies documented significant changes to our understanding of fault location, geometry, or activity. We added 9 new fault sources that meet the criteria of (1) a length ≥7 km, (2) evidence of recurrent tectonic Quaternary activity and (3) documentation that is publicly available in a peer-reviewed source. The prior models only included 6 fault sections and 10 fault zone polygons (previously called repeating large magnitude earthquake (RLME) polygons) in CENA. The revised databases include 15 fault sections and 10 fault zone polygons. Updates to the fault sources constitute a 150% increase in fault sections, but no change in the number of fault zone polygons, although fault zone polygons differ from RLME polygons used in prior models. No fault sources were removed from past models. Several seismic zones and suspected faults were evaluated but not included in this update due to a lack of current information about fault location, geometry, or recurrent Quaternary activity. These updates to the fault sections, fault zone polygons and earthquake geology databases will help inform fault geometry and activity rates during upcoming model implementation.

The Potential Impact of Listric Faults on the National Seismic Hazard Maps

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For the USGS National Seismic Hazard Maps, a fault dip distribution of 35°(0.2)-50°(0.6)-65°(0.2) has been assumed for Basin and Range normal faults following a 2012 recommendation of the Basin and Range Province Earthquake Working Group. In contrast, it has been suggested that the 2020 M 5.7 Magna, Utah earthquake occurred on a listric portion of the Salt Lake City segment of the Wasatch fault, which dips westward beneath the Salt Lake Valley. If this interpretation is correct, it would represent a paradigm shift in the characterization of the Wasatch fault zone and possibly other Basin and Range faults. Compared to moderately-dipping planar normal faults, listric or shallowly-dipping planar normal faults have higher ground-shaking hazard at hanging wall sites because the rupture distances are shorter and the hanging wall effects are amplified.

To illustrate the impact of fault geometry on seismic hazard estimates, we performed a probabilistic seismic hazard analysis (PSHA) for three representative sites in the Salt Lake Valley using both listric and planar Wasatch fault models. The PSHA results indicate that the seismic hazard for a listric Wasatch fault relative to that of a moderately-dipping planar fault increases with increasing distance from the surface trace of the Wasatch fault. On the west side of the Salt Lake Valley, the probabilistic ground motions for three different listric models compared to planar models with a dip distribution of 35°(0.3)-50°(0.5)-65°(0.2) increase up to 24% for peak horizontal ground acceleration and 31% for horizontal 1.0 sec spectral acceleration at a 2,475-year return period. Hence, if some or all of the Salt Lake City segment is listric, the National Seismic Hazard Maps underestimate the hazard in the western and central parts of the adjacent Salt Lake Valley. If other sections of the Wasatch fault or other Basin and Range faults are listric, the hazard has also been underestimated along parts of the adjoining valleys.

Update on the Implementation of Seismic Directivity Models Into the USGS National Seismic Hazard Model

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Our group recently began an effort to synthesize the community's work in the field of rupture directivity into a unified representation that can be implemented in the USGS National Seismic Hazard Model (NSHM). Currently, we are focusing on implementing a unified coordinate system into the NSHM code, in order to handle the added complexity needed for incorporation of several directivity models with hypocenter specification and complex fault geometry. We are also pursuing the near-term goal of simple adjustments to the ground motion median and standard deviation, before moving on to more complex approaches. These decisions follow from a workshop held in October of 2021 where invited speakers presented an overview of several directivity models and highlighted various efforts to incorporate rupture directivity effects into ground motion amplification adjustments and PSHA. In addition, the USGS Seismic Directivity Working group presented our plans and initial progress towards modifying future iterations of the NHSM. This included an overview of two main methods to consider as we advance: *Option 1*: spatially adjust the median ground motion and a corresponding correction in standard deviation from aleatory variability; *Option 2*: a hypocenter randomization approach, where the impact of multiple nucleation locations along a fault can be considered. The workshop was well-attended, and the community provided valuable feedback to consider moving forward. Some main takeaways include considering 1) complexities from multiple GMMs and their relation to directivity adjustments, 2) methods for handling complex multi-fault ruptures and 3) the potential bias from competing components affecting seismic hazard, such as basin amplification and other potential coupling effects. We plan to continue the open dialogue between the GMM developers and end-users regarding rupture directivity going forward and invite input on implementation options and future considerations.

Updating the USGS CEUS–WUS Attenuation Boundary—A Hazard Sensitivity Study

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The U.S. Geological Survey's National Seismic Hazard Model Project plans to release the next update to the National Seismic Hazard Model (NSHM) for the conterminous U.S. in 2023. One of the updates being considered is an alternative location for the central and eastern U.S. (CEUS)–western U.S. (WUS) attenuation boundary, the boundary that determines which type of ground motion model (GMM) is used for seismic hazard calculations. Currently, there is a boundary running through the eastern Intermountain West region, separating active tectonic WUS crust from stable CEUS crust. This boundary is used to separate earthquakes in the seismicity catalog into CEUS and WUS. When calculating hazard at a site from a given fault or seismicity grid cell, the GMMs appropriate for the source region (CEUS or WUS) are used (i.e., CEUS earthquakes are always used with CEUS GMMs). For a transition zone between 115- and 100-degrees west longitude (the overlap zone), rates of exceedances derived from CEUS and WUS GMMs are added together to compute total mean hazard. Recent studies of earthquakes in the overlap zone show that some of the areas classified as CEUS actually behave more like WUS GMMs. We have performed crustal attenuation tomography and stress drop studies in the region that support these findings and have proposed a new boundary that slightly modifies the area around the Colorado Plateau and includes the central and northern portions of the Central and Southern Rocky Mountains in WUS instead of CEUS. A sensitivity analysis compares sites in the overlap zone using the old boundary and the new proposed boundary. The proposed boundary may also be modified based on review comments from a public workshop in early 2022 or in the open public review period for the update to the NSHM. In the future, GMMs can be treated using alternative methods (e.g., dependence on the fraction of the paths in the CEUS and WUS).

Western US Geologic Deformation Model for Use in the US National Seismic Hazard Model 2023

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The U.S. National Seismic Hazard Model 2023 (NSHM23) requires a suite of deformation models built from geologic and geodetic data. A complete inventory of active faults is critical for deformation models. Of ~600 newly considered faults in NSHM23, we use author-reported values for ~200 faults to define the preferred, minimum and maximum slip rates as a triangular distribution for faults with slip rates determined from field studies. In preparation for the NSHM23 release, we updated the fault inventory to include an additional ~400 Quaternary-active faults that do not have direct measurements of their slip rates. Based on their geomorphic expression, most of these ~400 faults are categorized as slowly slipping faults in the USGS Quaternary Fault and Fold Database (QFFD) (0–0.2 mm/yr slip rate bin). Using slip rate categories assigned in the QFFD and a geodetic strain rate field as a guide, we constructed a geologic deformation model with assigned preferred geologic slip rates and associated uncertainty distributions for all faults considered in NSHM23. We find that assigning the mean value of the slowly slipping QFFD bin (0.1 mm/yr) exceeds the geodetically determined moment budget across the western U.S. Instead, to guide slip rate assignments, we subdivided the western U.S. into 22 tectonically similar subregions and assessed the geodetic strain rate within each subregion. We estimated the mean and uncertainty distribution of slip rates in the context of regional geodetic constraints. We then calculated geologic strain rates on each fault using multiple distribution shapes of geologic slip rates with the assigned QFFD slip rate bins as minimum and maximum values of the distributions. Finally, we computed geologic and geodetic moment across larger regions (n = 5) and observed that the geologic moment is generally less than the geodetic moment. The geologic deformation model, described here, will be evaluated and weighted alongside several geodetic deformation models to comprise the NSHM23 earthquake rupture forecast.

Adjoint Waveform Tomography: Methods and Applications

Oral Session · Friday 22 April · 2:00 PM Pacific

Conveners: Arthur J. Rodgers, Lawrence Livermore National Laboratory (rodgers7@llnl.gov); Qinya Liu, University of Toronto (qinya.liu@utoronto.ca); Michael Afanasiev, Mondaic Ltd. (michael.afanasiev@mondaic.com); Ryan Modrak, Los Alamoxs National Laboratory (rmodrak@lanl.gov)

Adjoint Tomography of the Hikurangi Subduction Zone and the North Island of New Zealand

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We use adjoint tomography, an imaging method which minimizes differences between observed and simulated seismic waveforms, to invert for three-dimensional structure of the North Island, New Zealand and the adjacent Hikurangi subduction zone. Starting from a ray tomography initial model, we perform 28 iterative model updates using spectral element and adjoint simulations to fit waveforms with periods ranging from 4–30 s. The updated velocity model improves data fit and introduces P- and S-wave velocity changes of up to ± 30%. A formal resolution analysis using point spread tests highlights that velocity changes are strongly resolved onland and directly offshore, at depths above 30 km, with low-amplitude changes (> 1%) observed down to 100 km depth. The most striking velocity changes in our updated model coincide with areas related to the active Hikurangi subduction zone, including: deep sedimentary basins in Cook Strait, velocity structures at depth related to the Taupō Volcanic Zone and previously-unidentified lower-plate anomalies interpreted as deeply-subducted seamounts and fluids within the downgoing slab.

The Lithospheric Structures Beneath Central and Southern Appalachians Revealed by Joint Full-waveform Inversion of Ambient Noise and Teleseismic Data

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The Appalachians is a passive continental margin located at the east of the North America continent which has gone through several stages of collision and splitting in geological history, first through formation and breakup of the Rodinia and then the formation and breakup of the Pangea. Therefore, the Appalachians provide a good example to study the continental collision process.

In central Appalachians, recent magmatic activity (e.g., Mazza et al., 2014, 2017) and topography rejuvenation (e.g., Miller et al., 2013) suggest possible effect from mantle. In Southern Appalachians, the suture zone of Laurentia and Gondwana collision (Hoppers er al., 2017) is well studied, while how the collision affected upper mantle is not clear. Therefore, high-resolution imaging of the structures of crust and lithospheric mantle beneath the Appalachians is crucial to understand the links between the crust and mantle structure.

Full-waveform inversion (FWI), with more accurate 3D numerical modelling of seismic wavefield, 3D sensitivity kernels as well as iterative inversion procedures aimed at reducing the misfit between data and 3D synthetics, is a powerful tool to investigate the subsurface structures. FWI based on ambient-noise data may help resolve the fine-scale crust structures and FWI based on high-frequency P waves and their coda/scattered waves can be applied to reveal small-scale heterogeneities and sharp interfaces in the lithosphere based on hybrid modelling techniques such as SEM-FK. The joint inversion of ambient noise data and teleseismic P waves may utilize the complementary sensitivity of these two datasets and provide improved resolution for the lithosphere (Wang et al., 2021).

For the MAGIC array (Long et al., 2020) and SESAME array (Parker Jr et al., 2013) deployed across the Appalachians to map the crust and uppermost mantle structures, we applied the joint FWI of ambient noise data and teleseismic data to map the Vs structures beneath the Appalachians. Our model identifies strong lateral heterogeneity in the crust and lithospheric mantle and may provide new constraints on the local geological process.

SASSY21: A 3D Seismic Structural Model of the Lithosphere and Underlying Mantle Beneath Southeast Asia from Multi-scale Adjoint Waveform Tomography

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We present the first large-scale seismic structural model of the lithosphere and underlying mantle beneath Southeast Asia obtained from adjoint waveform tomography (often referred to as full-waveform inversion or FWI), using seismic data filtered at periods from 20 - 150 s. By simulating the 3-D wavefield, FWI can account for the true physics of seismic wave propagation and is thus especially suitable for strongly heterogeneous regions such as Southeast Asia. Based on > 3,000 h of analyzed waveform data gathered from ~13,000 unique source-receiver pairs, we image isotropic P-wave velocity, radially anisotropic S-wave velocity and density via an iterative non-linear inversion that begins from a 1-D reference model. At each iteration, the full 3-D wavefield is determined through an anelastic Earth using the spectral-element solver *Salvus*, accommodating effects of topography, bathymetry and ocean load. Our data selection aims to maximize sensitivity to deep structure by accounting for body-wave arrivals separately.

SASSY21, our final model after 87 L-BFGS iterations across seven period bands, reveals detailed anomalies down to the mantle transition zone. The most prominent feature is the Australian plate descending beneath Indonesia, which is imaged as one continuous slab along the 180-degree curvature of the Banda Arc. Furthermore, the tomography confirms the existence of a hole in the slab beneath Mount Tambora and locates a high S-wave velocity zone beneath northern Borneo that may be associated with subduction termination in the mid-late Miocene. A previously undiscovered high-velocity feature beneath the east coast of Borneo is also revealed, which may be a signature of post-subduction processes, delamination or underthrusting from the formation of Sulawesi.

WUS256: An Adjoint Waveform Tomography Model of the Western United States for Improved Waveform Simulations

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We report a new model (WUS256) of the three-dimensional seismic structure of the crust and upper mantle structure of the Western United States (WUS) obtained by adjoint waveform tomography. The model resolves radially anisotropic shear and compressional wavespeeds and density using a multiscale inversion approach with 256 iterations based on trust region L-BFGS model updates. We started by inverting long-period waveforms in the band 50-120 seconds and progressed to shorter minimum periods of 40, 30, 25 and 20 seconds. The WUS256 model reproduces major features seen in recent tomographic studies, but often with stronger and more concentrated shear wavespeed (VS) anomalies. For example, the Cascadia slab and Isabella Anomaly appear as high VS features and the Yellowstone Hotspot, Snake River Plain, Gorda and Juan de Fuca Plates, Walker Lane and Geysers Clear Lake appear as low VS features. Variations in shear wavespeed and anisotropy with depth increase with inversion iterations and show stronger heterogeneity than other models. The resulting model shows significant improvement in the waveform fits over the starting and other models. In particular, the resulting model improves the fit to dispersed and scattered shorter period surface waves. We quantify the improvement in waveform fit by showing the relative reduction in both time-frequency phase (TF) and pointwise root-mean square (L2) misfits between the starting and inversion models. In fact, the WUS256 model reduces the mean TF and L2 misfits for both the inversion and an independent validation data set by a comparable amount (>60% and >50%, respectively). The improvement in waveform fit indicates that the model can be used to reproduce path effects on regional complete waveforms and moment tensor inversions. Further improvements are needed to resolve upper crustal structure (e.g. sedimentary basins) with shorter period data.

The Collaborative Seismic Earth Model: Generation 2

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We present the second generation of the Collaborative Seismic Earth Model (CSEM), a multi-scale global tomographic Earth model that continuously evolves via successive regional and global-scale refinements. Given finite computational resources, the CSEM enables a framework for Earth model construction by virtue of a systematic group effort. It thereby takes advantage of the distributed human and computing power within the seismological community. The basic update methodology makes use of the current CSEM as an initial model for regional tomographies to consistently incorporate previously accumulated knowledge into each new version.

The latest generation of the CSEM includes 20 regional refinements from full seismic waveform inversion, ranging from several tens of kilometers to the entire globe. Some noticeable changes since the first generation include detailed local waveform inversions for the Central Andes and Iran, continental-scale refinements for Africa and China and a global long-period tomography in new areas having no previous regional coverage.

Using a global full-waveform inversion ensures that regional updates do not conflict with whole-Earth structure. Across all regional refinements in the current CSEM, three-component waveform data from 1,637 events and over 700,000 unique source-receiver pairs are utilized to resolve subsurface structure. Minimum periods for subregions of the multi-scale model range between 55 to 8 seconds.

In this contribution, we will present the CSEM updating scheme and its parameterization, as well as the current state of the model. Active participation in the project is encouraged.

A New Model of the Australasian Region From Adjoint Tomography

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We present a new 3-D Earth model for crust and upper mantle structure of the Australasian region derived from full-waveform adjoint tomography and highlight several recent methodological advances.

To minimize the dependence on a-priori information, we start from a smooth 1-D background model without any knowledge of 3-D variations in crustal structure, Moho topography, or radial discontinuities. This model is generated from an auxiliary optimization problem that aims to find an optimal 1-D profile that fits surface wave dispersion curves in the starting frequency band.

The proposed inversion procedure follows the common multi-stage practice of starting with long-period waveform data and subsequently refining the frequency band to shorter periods. Anisotropic wavelength-dependent smoothing and model updates computed with a stochastic trust-region method effectively mitigate local minima and imprints of the events, and thus avoid the need for 3-D information in the prior. To reduce the characteristically high memory requirements of adjoint-based gradient computation, we also explore optimal checkpointing techniques and novel compression strategies.

A three-tiered strategy is applied to validate the resulting model and performance: (1) quantifying waveform fits using an independent set of validation events that have not been used in the inversion, (2) comparing the model to the final model of an inversion starting from AuSREM, (3) multi-period resolution tests utilizing Hessian-vector products obtained from the L-BFGS approximation.

Using K-means Clustering to Compare Adjoint Waveform Tomography Models of California and Nevada

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Full waveform inversion models represent the most detailed seismic tomography models currently available. However, the influence of starting models on final inversion results is rarely studied. To study this influence, we present three adjoint waveform tomography models of California and Nevada using three different starting models: the SPiRaL global model (Simmons et al., 2021), the CSEM_NA model (Krischer et al., 2018) and the WUS256 model (Rodgers et al., 2022). The three adjoint waveform tomography models use the same dataset of 103 events between magnitudes 4.5 and 6.5 that occurred from January 1, 2000 to October 31st, 2020. For each event, 175-475 stations record data, creating dense path coverage over California. The model iterations are computed using Salvus. We start running iterations for each starting model at 30-100 seconds period, gradually decreasing the period band

to 25-100 seconds and then 20-100 seconds. Over all period bands, we run more than 55 iterations and see misfit reductions of up to 40% in some period bands. Though structural details for each model vary and seem to correlate to differences in the starting model, all models provide waveform fits that fit the data equally well. Therefore, to test whether we could arrive at an analogous 3D model regardless of starting model (i.e. settling in a common global minimum), we utilize k-means clustering to analyze the similarities in large-scale structure in all three models. We separate each model into a crustal layer (0-30km depth) and uppermost mantle layer (30-150km), then run a k-means clustering algorithm on absolute Vs wavespeeds and anisotropy. We show that regardless of the differences seen visually, all three models resolve tectonic-scale structures with equal veracity.

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Regional Experiments on Source-encoded Adjoint Waveform Tomography

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We present a source encoding method that significantly increases the speed of adjoint waveform tomography. The technique enables the kernels to be computed with only one forward and one adjoint simulation regardless of the number of sources or receivers. In the meantime, it perfectly eliminates crosstalk noise between different sources and does not require each source to be received by all receivers. This is accomplished by assigning each source a unique frequency and measuring only the stationary part of the seismograms. We demonstrate the effectiveness of this method through 3D regional synthetic experiments. The region of interest covers parts of North America, Asia and Europe. We selected 988,152 traces from 786 earthquakes recorded at 9,825 stations. Based on ~20 inversions, each containing 30 iterations, we show that the kernels computed using this method are good enough to ensure a steady decrease of model misfit and determine the best choice of the objective function, preconditioner and optimization method.

Accelerating Full Waveform Modeling and Inversion With Neural Operators

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Full waveform modeling is a powerful tool for fine-tuning Earth structure models and understanding earthquake source processes, but it is computationally expensive. Here, we explore a prototype framework for accelerating full waveform modeling using a recently proposed machine learning paradigm called neural operator. We train neural operators on an ensemble of simulations performed with random velocity models and source locations. Once trained, the neural operator can simulate the wavefield at negligible cost for any velocity structure or source location. Due to the grid-free nature of neural operators, it is possible to evaluate solutions on higher resolution than the velocity models they are trained on, providing additional computational efficiency. We illustrate the method with the 2D acoustic and elastic wave equations. We also demonstrate the method's applicability to seismic inversion using reverse-mode automatic differentiation to compute gradients of the wavefield with respect to the velocity structure.

Automatic Differentiation for Seismic Inversion

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Seismic inversion is commonly used to constrain earthquake parameters of the Earth, such as its internal structure, that cannot be measured directly but instead must be inferred from observations. In contrast to complex geophysical inversion procedures, such as the adjoint-state method, modern deep learning frameworks (e.g., Tensorflow) can automatically optimize neural networks without the need for case-by-case derivation and implementation. To fill the gap between these two fields, we developed a general seismic inversion framework using automatic differentiation called ADSeismic. We have demonstrated its ability to solve problems of velocity model estimation, rupture imaging, earthquake location and source time function retrieval within a unified framework. This inversion framework further enables the optimizing of both neural networks and PDEs using automatic differentiation. To this end, we developed a new inversion method, NNFWI, to integrate neural networks (NN) into full-waveform inversion (FWI) by reparametrizing the velocity model with a generative neural network. NNFWI demonstrates the successful combination of the feature learning capability of deep neural networks with the high accuracy of PDE solvers to improve geophysical inversions. The generative neural network also provides a new regularization approach based on Deep Image Prior and a new uncertainty quantification approach using the Monte Carlo dropout technique to make inversion results more robust to local minima (cycle-skipping) and more stable for noisy seismic data.

Adjoint Waveform Tomography: Methods and Applications

Poster Session · Wednesday 20 April · Conveners: Arthur J. Rodgers, Lawrence Livermore National Laboratory (rodgers7@llnl.gov); Qinya Liu, University of Toronto (qinya.liu@utoronto.ca); Michael Afanasiev, Mondaic Ltd. (michael.afanasiev@mondaic.com); Ryan Modrak, Los Alamoxs National Laboratory (rmodrak@lanl.gov)

Finite-frequency Kernels for Pg Phases

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A major seismological challenge is to determine the short wavelength structure of the crust and uppermost mantle on a regional scale. The difficultly arises from trying to decipher the complex wave train known as Pg which consists of waves that reverberate in the crust. Pg is affected by the presence of large velocity gradients and discontinuities in the crust as well as layer interfaces and the free surface. Past tomographic studies of the crust and upper mantle have infrequently used Pg because of its observed variability, complexity and waveguide character. In this study, we attempt to improve our understanding of Pg wave propagation by calculating travel-time sensitivity kernels within different crustal models at 2s dominant period using the adjoint method. Our results show that Pg sensitivity kernels have complicated structure even with simple models and show notable variability with respect to layer velocities, interface smoothness and frequency passband. The sensitivity kernels confirm that Pg is made up of reverberating wave-guided body waves with dominant sensitivity in the middle crust. The kernels show clear differences in sensitivity between the upper, middle and lower crust. This suggests that modelling Pg sensitivity as a ray bouncing between the surface and the MOHO is a poor approximation. We found that lower-crustal waveguide modes are poorly represented by rays because they fail to account for the loss of energy to the mantle via diffraction. We conclude that full-waveform approaches would be helpful to accurately model Pg phases. LA-UR-22-20159

Full 3D Fréchet Kernels for Low-frequency Slowness Perturbations Measured Across Seismic Arrays

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Full three-dimensional tomography (F3DT) is a computationally demanding technique to image Earth structure by iteratively assimilating waveform constraints into 3D seismic velocity models. We seek to improve F3DT estimates of near-surface crustal structure by measuring frequency-dependent slowness perturbations across regional seismic networks and inverting these differential slowness data for subarray structure. The specific problem we address is how to calculate the Fréchet kernels that relate 3D velocity perturbations to 2D slowness perturbations using the full Rytov theory; i.e., without the local 1D approximation often assumed in Helmholtz tomography. Such vector-valued kernels can be written as linear combinations of scalar-valued spatial ker-

nels for single-station phase-delay measurements. We test our methodology on waveforms from regional earthquakes recorded by the Southern California Seismic Network (SCSN). We calculate synthetic waveforms for the CVM-S4.26 F3DT model (Lee et al., 2014) up to 0.2 Hz using the Hercules Toolchain of Tu et al. (2006), focusing on station arrays in the Los Angeles region. We measure single-station phase-delays using a GSDF procedure adapted to the array geometry, and we linearly combine their Fréchet kernels to obtain kernels for the centroid phase delay and the two components of the slowness vector. We show that, for arrays of 10 or so neighboring SCSN stations (apertures ~25 km) recording earthquakes at epicentral distances of ~250 km, the low-frequency slowness kernels are fairly localized in the vicinity of the array and that the sensitivity of the slowness perturbations to near-source and along-path structure is substantially reduced relative to the centroid phase-delay kernel. Our calculations indicate that incorporating slowness measurements into F3DT studies can increase the resolution of near-surface structure, especially in deep sedimentary basins.

Observations of Inner Core Shear Waves With AlpArray

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Although the solidity of Earth's inner core is evidenced by normal mode data, the direct observation of inner core shear waves (J-waves) has remained challenging for decades due to their small amplitudes. Previous studies have presented evidence of J-waves in different seismic datasets (e.g., *Okal and Cansi Y*, 1998; *Deuss et al.*, 2000; *Cao et al.*, 2005; *Wookey and Helffrich*, 2008), however, the observability seems to be highly dependent not only on distance, but also on the location of the source and receiver, suggesting that amplification from specific three-dimensional structures in the deep Earth is necessary to elevate the phase above noise for certain ray paths. *Waszek and Deuss* (2015) and *Tkalčić and Phạm* (2018) also found J-waves in global stacks and global correlation wavefield respectively, but these average over all possible source-receiver geometries and inner core structure.

To improve phase identification and discrimination, we use an approach that combines the array method of slant stacking and polarization filtering to enhance linearly polarized signals with the expected slowness and incident angle. We apply this technique on the data of the AlpArray Seismic Network, a large-scale seismic network in Europe that consists of over 600 broadband stations with a mean station spacing of 30-40km. An arrival consistent with PKJKP (in reference travel time, slowness, and polarization) is found from events in the source region reported by *Cao et al.* (2005). We present an overview of PKJKP candidate paths over distance based on observations with AlpArray. We also examine whether these observations correspond to specific depths or azimuths and investigate the effects of anisotropy or other three-dimensional earth structures.

Scattered Wave Imaging of Lithospheric Discontinuities: Eliminating Moho Reverberations With Radon Filters.

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Global maps of upper mantle discontinuities are often constructed using the popular technique of receiver functions (RF) – source-deconvolved seismograms that target seismic structure directly underneath a seismic array. These maps have provided fundamental constraints on the origin and character of mid-lithosphere discontinuities in the continents and of the global lithosphere asthenosphere system. Although the horizontal receiver function (Ps-RF) technique has been widely successful for crustal imaging, it has seen limited use in continental-scale lithospheric imaging due to signal distortion caused by overprinting of Moho reverberations. For this reason, the vertical receiver function (Sp-RF) is preferred; even though it has a lower resolution (low frequency and sparser data sampling). In this study, we introduce an RF decomposition technique using non-linear Radon filters (NRF). This technique can eliminate Moho reverberations from Ps-RFs allowing sharper images of upper mantle discontinuities to be obtained. We demonstrate, using synthetic and data examples obtained from large North American seismic arrays, how the NRF enables us to obtain sharper and cleaner images of mid-lithosphere discontinuities.

The non-linear Radon inverse transformation of the input receiver functions decomposes the signals into its underlying wavefield contributions – direct conversions, multiple reflections and noise. A suitable filter is then applied in the Radon domain to separate plane waves based on their unique travel-time moveout. This is crucial to separating and eliminating unwanted signals and retrieving desired signals. The cleaned RFs are then transformed into the data domain by applying a forward Radon transform now free of the undesired Moho reverberations. Preliminary results based on the application of this method on synthetic receiver function show that reverberations have a significant impact on the raw receiver function stacks.

Seismic Wavefield Simulations of 3D Anisotropy in a Mantle Wedge Setting

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There is compelling evidence for seismic anisotropy within the subducting plate, the mantle wedge and the crust. Moreover, different regions of a mantle wedge may have different anisotropic structures. When an earthquake occurs, this complex anisotropic structure manifests itself on seismograms. A widely used method to study subsurface anisotropy is that of measuring the splitting of shear waves from global as well as local earthquakes. It is challenging to link a surface observation of shear wave splitting with a subsurface structure, because several characteristics are needed: the location of the structure, the strength of the perturbation and the type of anisotropy (e.g., tilted transverse isotropy). Here we perform numerical simulations using different anisotropic and realistic mantle wedge settings, including the Alaska subduction zone. We also examine the frequency-dependent influence of different types of anisotropy within the mantle wedge on synthetic seismic waveforms. We also hope to identify misfit measures that are amenable to 3D anisotropic tomographic inversions. Our long-term goal is to perform an adjoint-based anisotropic tomographic inversion in the Alaska subduction zone.

The Effect of Mantle Corrections on SmKS Measurements

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Improving the uppermost outer core structure is crucial for understanding the interaction between the mantle and core, the generation of the Earth's magnetic field and the thermochemical exchange in the core-mantle boundary (CMB). Mantle corrections are commonly applied to core phases, such as SmKS phases, to reduce the complexity of seismic waveforms due to 3D mantle and crustal heterogeneities in illuminating the core structure. In this study, we use synthetic seismograms computed for 1D and 3D Earth models by the 3D global seismic wave propagation solver SPECFEM3D_GLOBE (Komatitsch and Tromp 2002) to assess how well mantle corrections work. To this end, we generate synthetic seismograms for about 50 globally distributed earthquakes within the moment magnitude range 5.8-6.5 using the radially symmetric isotropic PREM (Dziewonski and Anderson 1981), 3D mantle model S40RTS (Ritsema et al. 2019) with 3D crustal model Crust2.0 (Bassin et al. 2000) (S40RTS+Crust2.0), S40RTS with 1D PREM crust (S40RTS+1DCrust) and 3D mantle and crustal models GLAD-M15 (Bozdag et al. 2016) and GLAD-M25 (Lei et al. 2020). We systematically measure traveltimes and amplitude anomalies between PREM and 3D SKS and SKKS waveforms. We then compute phase shifts for each source-receiver pair due to 3D models by a ray-tracing algorithm and compare them with those measured directly from synthetic waveforms to assess how well we estimate the crustal and mantle phase in mantle corrections. We will present our preliminary results and discuss the robustness of mantle corrections in outer-core studies.

Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science

Oral Session · Thursday 21 April · 8:00 AM Pacific

Conveners: Sarina C. Patel, University of California, Berkeley (sarina.patel@berkeley.edu); Stephen Crane, Natural Resources Canada (stephen.crane@nrcan-rncan.gc.ca); Fabia Terra, University of California, Berkeley (terra@berkeley.edu); Mouse Marie Reusch, Pacific Northwest Seismic Network (topo@uw.edu)

A First Look at Earthquake Early Warning in Alaska

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The goal of this study is to provide initial considerations for early warning tailored to the tectonics Alaska.

Active tectonics between the Pacfic and North American plates make Alaska one of the most seismically active areas in the world. While many of the large earthquakes in Alaska happen offshore, along the Aleutian Islands, events also occur inland at deep tectonic interfaces and numerous fault systems in the crust. These earthquakes pose serious hazards. History demonstrates this clearly. Implementing an earthquake early warning system tailored for Alaska's unique seismic setting is an inevitable development both through corporate entities and as an extension of the current early warning systems along the US west coast.

We use a scenario-based approach to examine the trade-offs between ground motion and initial warning time for a variety of realistic earthquakes. Our warning time estimates are derived from the current network of seismic stations and simple traveltime estimates. We use ShakeMap to forward model the ground motions. We present relationships between warning time, intensity of shaking and different earthquake characteristics, such as depth, magnitude, location and proximity to significant population. These findings illustrate the types of scenarios that should be addressed as we begin to consider what early warning in Alaska might look like.

Rollout of the Metro Vancouver Network-based Earthquake Early Warning System

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The network-based EEW system for the Greater Vancouver Water District (GVWD) was designed and installed in 2021 as part of the project "EEW and Strategic Response System". The project delivered not only an EEW application but also a Structural Health Monitoring (SHM) service for the critical infrastructure operated by GVWD. The project builds on a decade-long experience of operating a number of on-site early warning systems protecting various public and private facilities in British Columbia, Washington and Oregon.

The system architecture employs a distributed computing framework and is designed to use a client-server model. To minimize false positives and corresponding expensive downtime, each station incorporated an advanced algorithm for detection and discrimination of P waves. To ensure robust, secure, and fast message passing over the WAN/Internet, a novel protocol was developed. The size of the packets sent to the server is minimized by pre-computing the vector of the event parameters at the client side. The server side aggregates information from each client and computes the final set of the event parameters using the assumption of a point-source model.

Soon after installation, the network recorded its first earthquake on December 17th, 2021. It was a M3.6 event with an epicentral distance ~50km. The magnitude and the epicenter coordinates were identified within the expected error bounds. Based on the predetermined design and triggering criteria no alarms were issued, however, the SHM dashboard successfully visualized post-event structural health information of the operating facility.

Towards Public Earthquake Early Warning Across Central America

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In Central America, devastating ground shaking from large subduction earthquakes and moderate shallow crustal earthquakes close to cities can be expected to cause widespread collapse of infrastructure. As the earthquake risk increases due to the rise of population density, and in the absence of significant initiatives to improve the building stock, alternative ways to mitigate the risk to the vulnerable populations should be a priority. An Earthquake Early Warning (EEW) system coupled with rapid public distribution and appropriate response training, can allow the population and decision makers to take actions that reduce injuries and fatalities from damaging shaking. National seismic networks in Guatemala (INSIVUMEH), El Salvador (MARN), Nicaragua (INETER) and Costa Rica (OVSICORI-UNA) are collaborating with SED/ETH-Zurich to build and operate EEW in the ATTAC project (Alerta Temprana de Terremotos en América Central). At its core, the EEW system operates on the existing high quality seismic networks and implements the ETHZ-SED SeisComP EEW (ESE) system with the Virtual Seismologist and the Finite-Fault Rupture Detector algorithms. We report on the status of EEW in the region. To date, the ESE system has been running in 3 centers; densification of the seismic monitoring networks with 71 EEW-ready accelerographs has been completed; training for improving network practice and operating EEW software has been provided across the region; and test users get alerts from an alert dissemination platform using emerging digital TV technology that can scale to the population. We analyze EEW performance and demonstrate significant warning times before S wave arrival from shallow earthquakes on-shore and near-shore routinely identified within 10–20 s of their origin times. Within the next 2 years, we aim to operate public EEW in at least one participant country and to create long-lasting governance mechanisms within each nation that can support EEW after the project is concluded.

From Real-time Earthquake Monitoring to Earthquake Early Warning in Switzerland

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The Swiss Seismological Service (SED) at ETH Zurich has developed and maintained a national Earthquake Early Warning (EEW)-ready seismic monitoring infrastructure in Switzerland based on the Swiss Seismic Network and the SeisComP monitoring platform. We have built a comprehensive set of SeisComP modules that can provide EEW solutions using the Virtual Seismologist (VS) and Finite-Fault Rupture Detector (FinDer) EEW algorithms. These methods can provide EEW for moderate to great events, provided that they can rely on a high quality, EEW-ready, seismic network. VS provides EEW magnitudes for point-source origins that can be provided by SeisComP as soon as events are detected by 4 stations. FinDer infers in real-time the on-going finite-fault rupture extent by matching modeled templates against the growing patterns of observed high-frequency seismic acceleration amplitudes. In observed real-time performance, the median delay for the first VS alert is 8.7s after origin time (56 earthquakes since 2014, from M2.7 to M4.6) and 7s for FinDer (10 earthquakes since 2017, from M2.7 to M4.3), accounting for a median P-wave travel time of 3.5s from event origin to the fourth station. On average, stations in Switzerland have a 1.4s data sample latency. Operating two similarly fast independent algorithms offers redundancy and tolerance to failures of a single algorithm. The ETHZ-SED SeisComP EEW system achieves performance that is comparable to other operational EEW systems around the world.

CrowdQuake+: Noise-robust and AI-empowered Earthquake Early Warning Using Low-cost MEMS Sensors

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Recently, IoT systems have been widely developed for earthquake detection because of the easy construction of a dense seismic network, communication capabilities and low cost of sensors. However, when utilizing MEMS sensors as a seismic sensor, earthquake detection capabilities are often affected by noises because such sensors are installed in places where are exposed to various types of noise sources. Furthermore, the time gaps between P-wave and S-wave are often short in these seismic networks because sensors are usually located near an epicentre due to the highly dense seismic network. As a result, to detect an earthquake in such systems, different detection approaches are required. In this study, we present CrowdQuake+, an IoT-based seismic system, which provides a dense seismic network incorporating low-cost MEMS accelerometers and deep learning-based detection algorithms. To deal with various environmental noises, our detection algorithm is comprised of a traditional triggering algorithm and two deep learning classifiers to detect P-wave and S-waves within a few seconds. Our 2-phase strategy can classify earthquakes from noises after an initial trigger detected by STA/LTA and then a deep learning model (P-detector) detects a P-wave within 2 seconds followed by another multi-headed convolutional neural network (MCNN) to classify the S-wave of the earthquake using a 2-second input waveform. P-detector is trained on noises and 4-seconds input which contains approximately 2-second P-wave segments and MCNN is trained on noises and 2-second maximum accelerations. Through 1-year of operations, our CrowdQuake+ detected several earthquakes ranging M 2.5 and M 4.9 earlier than a traditional seismic network. Specifically, in the recent M 4.9 earthquake in South Korea, CrowdQuake+ monitored ground motions on over 110 of 130 sensors within 40km and successfully classified P-waves and S-waves on about 90 sensors. Also, our results show that CrowdQuake+ can be more effectively improved for earthquake early warning when it is used with a traditional EEW system.

Seismic Station Expected Value Metrics for Earthquake Early Warning Networks

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Early warning (EEW) requires high-availability, low-latency seismic data delivery. Limits on funding require engineers and network sponsors to consider which investments in telemetry and stations are most effective in terms of mission and cost. We address this need by estimating station expected value, as a direct measure of its contribution to the EEW network. The spatial contribution of a network station can be measured from the area it improves and the reduction in alert time in that area (area-time metric, km^2-s). How often the station actually contributes depends on how often earthquakes occur nearby. Proxies have been proposed, such as USGS National Seismic Hazard Mapping Project (NSHMP) accelerations at a specified return time (Hotovec-Ellis et al., 2017; Owengo et al., 2019); for example, peak ground acceleration (PGA) at 2% in 50-year probability. We instead extract return times at a fixed acceleration from NSHMP gridded data. Return times (years) can be interpreted as the reciprocal of the expected participation rate (1/yr), i.e., how often the engineering benefit of the station or network component will contribute. Station expected contributions thus have units of km^2-s/yr. High values in the Southern California Seismic Network (SCSN) come either from normally spaced stations near active faults or widely spaced stations near lower activity faults. Stations with higher values are of greater value to the EEW network, e.g. these are the ones that you would spend more on to ensure they have high uptimes and good communication. Lower values correspond to dense portions of the network where individual stations contribute less. We illustrate the approach with ShakeAlert stations of the SCSN. Station expected value estimates provide a physically meaningful basis for deciding among investments in station and telemetry hardening and redundant communication systems.

Development of a Companion Questionnaire for 'Did You Feel It?': Assessing Response in Earthquakes to Include Earthquake Early Warning

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Earthquake early warning (EEW) systems are relatively new technologies having first emerged as regional systems within nations in the 1990s. Japan was the first to develop and implement a nationwide system in October 2007, and in the United States (US), ShakeAlert® became available on the entire length of the US West Coast in May 2021. Assessing how EEW is perceived and utilized by alert recipients is considered essential to effective implementation of EEW. Survey research in the aftermath of a significant earthquake in which an EEW has been issued is one obvious method of achieving these objectives, and there already exist a number of survey instruments for this purpose. A related strategy and the goal of the present research is to develop a brief questionnaire, consistent with those already developed, as a supplement to the United States Geological Survey's 'Did You Feel It?' questionnaire that has provided earthquake intensities and information on behavioral response in earthquakes, both domestic and international, since 2004. Knowing the shaking intensity level at each respondent's location is essential for relating their perspectives and actions to the shaking they experienced. Such assessments are necessary to evaluate whether alert recipients are taking advantage of alert messages to initiate protective actions upon receipt of an alert, how they regard the usefulness of alerts, what are the desirable thresholds for issuing alerts and other aspects of these systems. Having information from users will also facilitate assessments of the success of earthquake preparedness educational programs such as the ShakeOut and help determine whether annual drills, which include information on EEW systems, are resulting in behavioral response consistent with the content of these programs. Finally, information on EEW utilization will provide data useful to social scientists who study hazards to advance our understanding of behavioral response to warnings.

Exploring Evidence-based Guidelines for Protective Actions and Earthquake Early Warning Systems

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Earthquake early warning systems (EEW) are becoming increasingly available or in development throughout the world. With public alerting in Mexico, Japan, Taiwan, New Zealand, Philippines and the United States, among others, it is important to provide evidence-based recommendations for protective action so people can protect themselves when they receive an alert. Best-practice warning communication research suggests that providing a protective action will increase the efficacy of the message. However, given the diversity of earthquakes and building types, and social/cultural contexts that these systems exist in, the question is: what is the best protective action to recommend? In this research, we seek to answer this question by developing guidelines for consideration when deciding on what advice is best to provide.

We outline key lessons and influential theories from the social sciences and humanities that can be integrated into messaging for EEW systems. We then provide an overview of what is known about injuries and fatalities during earthquakes and review current protective action recommendations and associated public education campaigns. We explore three critical questions for operators of these systems regarding what protective action to recommend, thereby developing a guideline to assist decision makers of these systems. We explore our limitations and future directions for the research, including more data types that earthquake injury researchers can collect to help fill gaps in the literature.

We determined factors to consider include: 1) social, cultural and environmental context such as who people are with and their social roles and what type of building an individual is located in when an earthquake happens, 2) demographic variables such as gender, age and previous history with earthquakes and 3) magnitude and intensity that influence the duration and impacts of the earthquake itself.

Real-time Performance of the PLUM Earthquake Early Warning Algorithm for the West Coast of the US

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We summarize the real-time performance (July 2019-Present) of the Propagation of Local Undamped Motion (PLUM) earthquake early warning algorithm in California, Oregon, and Washington. PLUM is being tested for potential inclusion in the ShakeAlert system. The ShakeAlert system is currently based on two methods that estimate earthquake source parameters. PLUM is different, predicting expected ground motions from observed ground motions directly. The original algorithm was developed in Japan to complement source-based algorithms to address their deficiencies, such as missed or false alerts during complex sequences and limited to no warning times in the near source region. PLUM detects an event when two neighboring stations observe ground motions above defined trigger thresholds, then forward predicts those and subsequent ground motions to nearby regions. Retrospective testing of PLUM was used to optimize the configuration for the station distribution and levels of shaking targeted for alerts in the ShakeAlert system. Real-time testing of PLUM since July 2019 has allowed for further refinement of the algorithm. We used a primary station trigger threshold of Modified Mercalli Intensity (MMI) 4.0; the secondary station trigger threshold changed from MMI 2.5 to MMI 3.0 in Sept. 2020. We also increased the PLUM prediction radius from 30 km to 60 km to optimize performance when using the 0.2° by 0.2° ShakeAlert grid as alert regions. Soon after initializing, PLUM issued 11 false alerts (alerts not associated with an earthquake) caused by station noise and duplicate station data, but minor code changes and data quality checks eliminated all false alerts since July 2020. During the real-time tests PLUM alert grids accurately covered areas of shaking for all earthquakes of concern, including M6.4 & M7.1 Ridgecrest, M6.5 Monte Cristo, M5.8 Lone Pine, M5.1 & M6.2 Petrolia, M6.0 & M5.0 Antelope Valley. The median time from the origin to detection is around 6 seconds.

Superconducting Earthquake Early-warning Device (SEED) for Detection of Prompt Gravity Signals from Earthquake Ruptures

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The efficiency of current Earthquake Early Warning Systems (EEWS) is limited by their reliance on seismic waves to carry information about the earthquake source: the P-waves used for earthquake detection travel only moderately faster than the damaging S-waves, which limits the EEW lead time and creates a blind zone for EEW. Harms et al. (Geophys. J. Int. vol. 201, 1416, 2015) proposed to overcome this fundamental limitation by developing an EEWS based on geophysical signals that travel at the speed of light: the transient gravity signals generated by the dynamic solid Earth deformation induced by earthquakes. While gravity signals have been recently detected before P waves using broadband seismometers about 1 min after the rupture onset of M > 8 earthquakes, their expected amplitude at earlier times relevant for EEW is generally very small, much below the sensitivity of current instruments. Here we discuss the design and principle of a Superconducting Earthquake Early-warning Device (SEED) that could meet the target sensitivity proposed by Harms et al. (2015), 8×10^{-16} s^{-2} $Hz^{-1/2}$ at 0.2 Hz in gravity gradient spectral density.

The design of SEED will be based on the proven superconducting gravity gradiometer (SGG) technology. To reach the target sensitivity of SEED, which is two and a half orders of magnitude beyond that of our SGG under development, we will scale up the mass and baseline of the SGG and utilize a lower-noise Superconducting Quantum Interference Device (SQUID), which is now available commercially. SEED will consist of four magnetically levitated niobium cylinders with each test mass weighing 10 kg and a baseline of 1.0 m, cooled to 4.2 K by commercial cryocoolers and coupled to SQUIDs through capacitance bridges. By combining the outputs of the four three-axis accelerometers, a full-tensor gravity gradiometer can be constructed with isotropic sensitivity for gravity signals coming from any direction.

Real-time and Data-driven Ground Motion Prediction Equations for Earthquake Early Warning

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The ShakeAlert earthquake early warning system characterizes earthquake source locations and magnitudes in real time, issuing public alerts for areas where predicted ground motion intensities exceed a threshold value. While rapid source characterization methods have attracted a lot of attention in recent years, the ground motion models used by ShakeAlert have received significantly less. Since there are large uncertainties in earthquake source estimation, there is an immediate need for a flexible and EEW-tailored ground-motion model. This study seeks to develop data-driven framework for EEW-specific ground-motion models by pre-computing and incorporating site-specific corrections while using a Bayesian approach to estimate event-specific corrections in real time. The study involves analyzing 300,000 seismic recordings from ~1500 events (3> M > 8) from the entire state of California, for the period 2011 to 2021. This approach will enable the development of a novel ground motion prediction module that can automatically correct for inaccuracies in the earthquake source estimations as well as account for higher-order source features such as seismic stress drop. Not only will prediction uncertainties likely be decreased, but they can be tracked in real time so that they may be considered directly in ShakeAlert's alerting decision.

Detecting Earthquakes in Noisy Real-time GNSS Data With Machine Learning

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Real-time Global Navigation Satellite Systems (GNSS) data are an important source of information about earthquakes as they occur, as they do not saturate in the near field with high magnitudes as broadband seismic data do. For this reason, integration of real-time GNSS data into earthquake monitoring systems such as tsunami and earthquake early warning (EW) has been a subject of great interest. However, GNSS data have a much higher noise floor (~1-5 cm) than traditional seismic data, especially in real-time, making it difficult to identify the early onset signals of events. Here we show the performance of a machine learning algorithm for identifying earthquakes in real-time GNSS data by modifying an existing convolutional neural network (CNN) code designed for picking P-waves in seismic data. This CNN was trained using realistic synthetic earthquake waveforms modeled using the faults associated with the Ridgecrest Sequence, as well as real-time noise from the UNAVCO-operated Network of the Americas (NOTA) GNSS stations around Ridgecrest. From preliminary testing of the CNN using synthetic waveforms which it had never seen in training, the model's general success at identifying earthquakes is around 63% for the entire dataset. For waveforms with peak ground displacements (PGDs) between 1 and 10 cm, we achieve an accuracy of 69%, and for waveforms with PGDs between 10 cm and 1 m, we achieve an accuracy of 91%. We are working to improve our success rates by modifying the training process and the distribution of PGDs in waveforms used for training. We are also testing the algorithm using real UNAVCO NOTA position solutions to see how well it can identify the onsets of the major Ridgecrest earthquakes, as well as smaller foreshocks and aftershocks. These position solutions are the same types of data that an EW system would receive, so the success of this method could have implications for how real-time GNSS data are incorporated into earthquake monitoring systems.

Applications of Nonergodic Site Response Models to ShakeAlert Case Studies in the Los Angeles Area

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Parker and Baltay (2022) used ground motions from 414 M3-7.3 earthquakes in southern California to develop nonergodic site response models for the greater Los Angeles area. In this study, we explore whether these models can improve ground motion forecasts in the U.S. Geological Survey ShakeAlert™ Earthquake Early Warning system (hereafter ShakeAlert). We implement

the PGA and PGV site response models in ShakeAlert via the Eqinfo2GM module, which predicts ground motions from the estimated earthquake parameters of magnitude and location. We test partially non-ergodic ground motion forecasts for five earthquakes in the Los Angeles area: the 1994 M6.7 Northridge earthquake, the 2008 M5.4 Chino Hills earthquake, the 2019 M7.1 Ridgecrest earthquake, the 2020 M4.5 South El Monte earthquake and a synthetic M7.8 earthquake on the San Andreas Fault. From the test results, we find that with the nonergodic site response applied, ShakeAlert not only alerts larger areas, but can also result in longer warning times in Los Angeles. In addition, the Modified Mercalli Intensity (MMI) map generated by the ShakeAlert Eqinfo2GM module matches better with the corresponding ShakeMap ground truth MMI contours when the nonergodic site response model is applied.

Ground Motion Forecasting for Large Events With HR-GNSS and Deep Learning

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The ultimate goal of earthquake early warning (EEW) systems is to forecast strong shaking amplitudes before their onsets. The system relies on rapid and accurate estimation of earthquake source parameters. However, one of the existing challenges of EEW systems is that large earthquakes (Mw7.5+) have strong shaking that can clip near-field seismic sensors, and their long and complex ruptures, making them difficult to characterize rapidly and accurately with the commonly adopted scaling methods. In a previous study, we have shown the reliability of using a deep-learning model, called Machine-Learning Assessed Rapid Geodetic Earthquake model (M-LARGE), that directly tracks the evolution of earthquake magnitude from the near-field using high-rate GNSS data with a prediction accuracy of 99%, which provides a way to strengthen EEW systems' performance on large earthquakes. Here, we further expand the M-LARGE algorithm to predict centroid location and fault size in real-time, and use the predicted parameters to forecast strong ground motion. Our result on the 10,000 testing data and 5 real data shows an averaged high accuracy of 95% in the source parameters, which leads to accurate ground motion predictions for shaking intensity of MMI3+ and significant warning time from tens of seconds to minutes.

Exploring Two-station Alerting With Epic and Machine Learning Classifier

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Over the past 3 years we have been exploring the use of a machine learning classifier within the EPIC Earthquake Early Warning (EEW) algorithm. The first stage of research consisted of testing the classifier model on a new data-set, with waveforms that it hadn't seen before. The classifier appeared to work well with these new data, with high accuracies comparable to those seen when training the model. As the original model by Meier et al. (2019) used 3-sec of data after the trigger, which is significantly more than EPIC currently requires, we retrained the model using just 1-sec of data after the trigger to explore how the precision and recall would change. While the performance decreased slightly, overall the performance using 1-sec of data after the trigger appeared to be satisfactory. Following these performance evaluations, we began implementing the classifier within the EPIC algorithm. We created multiple version of EPIC with different logic, classifier models and required amounts of data. In order to evaluate the performance of these different versions of EPIC, we developed a review tool, based on the ShakeAlert DM Review Tool. This tool allowed for the easy comparison of the different versions. One of these test versions running the classifier allows alerts using just 2 stations instead of the 4 stations required by the current production version of EPIC. Allowing alerts using two stations may allow for faster alerts, particularly in areas of sparser station coverage. In this presentation, we present an overview of performance of these modified versions of EPIC.

Advances in Earthquake Early Warning: Research, Development, Current State of Practice and Social Science

Poster Session · Thursday 21 April · Conveners: Sarina C. Patel, University of California, Berkeley (sarina.patel@berkeley.edu); Stephen Crane, Natural Resources Canada (stephen.crane@nrcan-rncan.gc.ca); Fabia Terra, University of California, Berkeley (terra@berkeley.edu); Mouse Marie Reusch, Pacific Northwest Seismic Network (topo@uw.edu)

An Earthquake Early Warning System for the Lower Rhine Embayment, Germany

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The Lower Rhine Embayment in western Germany is one of the most important areas of earthquake recurrence north of the Alps, facing a moderate level of seismic hazard in the European context but a significant level of risk due to a large number of important industrial infrastructures. In this context, the project ROBUST aims at designing a user-oriented hybrid earthquake early warning and rapid response system where regional seismic monitoring is combined with smart, on-site sensors, resulting in the implementation of decentralized early warning procedures.

One of the research areas of this project deals with finding an optimal regional seismic network arrangement. With the optimally compacted network, strong ground movements can be detected quickly and reliably. In this work simulated scenario earthquakes in the area are used with an optimization approach in order to densify the existing sparse network through the installation of additional decentralized measuring stations. Genetic algorithms are used to design efficient EEW networks, computing optimal station locations and trigger thresholds in recorded ground acceleration. By minimizing the cost function, a comparison of the best earthquake early warning system designs is performed and the potential usefulness of existing stations in the region is considered as will be presented in the meeting.

Can PLUM Earthquake Early Warning (EEW) Ground Motion Estimates in Southern California Be Improved by Incorporating Empirically Derived Site-Term Corrections?

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The Los Angeles (LA) basin can shake like a bowl of Jell-O when excited by seismic waves, the reverberations greatly amplifying ground motions. Here, we explore if site terms empirically derived from recorded earthquake ground motion intensities can help account for these site-specific effects and improve the performance of the PLUM (propagation of local undamped motion) earthquake early warning algorithm. PLUM does not derive earthquake magnitude or location; it simply detects ground motions and alerts areas expected to exceed a threshold level. We use the site terms from Devin et al. (2022) that were derived using a database of 46,657 PGA and PGV values from 414 M3+ earthquakes in southern California. They used the Atkinson et al. (2014) intensity prediction equation to predict modified Mercalli intensity (MMI) for each record using magnitude and hypocentral distance, and then computed residuals. The residuals were partitioned into site, event and error terms using a linear mixed-effects analysis, generating 2009 site terms, from 30 networks, representing empirical amplification factors. These MMI site corrections have a normal distribution about zero, with a standard deviation of 0.4 MMI units, and extreme site term adjustments of ±2 MMI units.

We test the usefulness of incorporating site terms into PLUM using M3.5+ earthquakes in southern California. We apply these site corrections to observed MMI ground motions and evaluate if the adjusted MMI values affect the PLUM detection algorithm, in both speed and accuracy. Secondly, we apply the MMI-based site adjustments to the outward prediction points using a V_{S30}-MMI relation from Devin et al. (2022), and compare how the PLUM ground-motion predictions compare to ShakeMap MMIs, which are assumed to be the ground truth. Initial tests using the 2014 M5.1 La Habra data show that, on average, when using the site terms the predicted MMI improves by ~0.5 MMI units in the alerted region.

Earthquake Location Performance of ShakeAlert's Epic Algorithm for Recent Offshore Events Near Cape Mendocino, California

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Over the past three years, the ShakeAlert earthquake early warning (EEW) system has provided timely alerts of earthquake shaking for residents in California. These alerts are crucial for people in areas where potentially damaging shaking will occur, as it allows them to proactively take cover and mitigate their earthquake risk. As ShakeAlert continues to grow, it is important to assess its performance in seismically challenging environments. One such environment that continues to pose a challenge for EEW is offshore of California's coast. Due to the low density and one-sidedness of station coverage, rapid earthquake location algorithms mislocate offshore events with an average higher offset than on-shore events of the same magnitude. The mislocation of large offshore earthquakes means when a damaging earthquake does occur, the wrong people may be alerted, or no alert may be sent at all. This potential scenario erodes the confidence of users, lessening the urgency of the next alert. In this study we evaluate the performance of ShakeAlert's EPIC location algorithm for offshore earthquakes near Cape Mendocino over the past 3 years. Over this time, there have been numerous earthquakes with magnitudes greater than 4 within the Mendocino Fracture Zone, including the 20 December 2021 M6.2 Petrolia earthquake. We highlight both cases where ShakeAlert accurately located offshore events, as well as cases where it mislocated events. We also highlight potential changes that could be made to the location algorithm to improve offshore location uncertainty.

Enabling Inclusion of Magnitude Estimates Based on Peak Ground Displacement in the ShakeAlert Solution Aggregator

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Real-time GNSS data can provide non-saturating magnitude estimates via the scaling between peak ground displacement (PGD) and source-station distance. This method is part of an algorithm, GFAST, which is under development for use in the ShakeAlert Earthquake Early Warning System. Currently ShakeAlert combines magnitude estimates from two seismic algorithms in the Solution Aggregator (SA) which determines whether to use both estimates and, if so, computes their weighted average. We present a means for including PGD-based magnitude estimates (Mpgd) in the SA by 1) establishing a criterion to determine when GFAST issues a Mpgd estimate and 2) estimating Mpgd uncertainty for use in the weighted average.

PGD is the norm of the difference between the current epoch's horizontal or 3D position and a reference value which is typically the average position over a time window immediately preceding an earthquake origin time (OT). Due to colored noise in real-time GNSS position estimates, PGD drifts to higher values with time from the reference epoch. Thus, Mpgd increases with time past-OT. We find that in the absence of an earthquake typical mean and 99th percentile 3D PGD computed after 20 seconds are 5 and 18 cm, respectively; these increase to 7 cm and 24 cm by 30 seconds past the reference epoch. The mean and 99% Mpgd computed from these noise-only positions are 6.1 and 6.7, respectively, after 20 seconds and 6.3 and 6.9 after 30 seconds. We applied GFAST to a large dataset of real-time 1 Hz GNSS positions recorded in the absence of earthquakes to characterize Mpgd as a function of time since the earthquake, station density, and data processing method. The resulting suite of PGD and Mpgd estimates underpin a criterion defined by PGD threshold to control when GFAST issues Mpgd estimates and an empirical approach to assigning Mpgd uncertainty. We evaluate whether including Mpgd in the SA with this approach improves magnitude estimates using data from the ShakeAlert test suite.

How Low Should We Alert? Quantifying Intensity Threshold Alerting Strategies for Earthquake Early Warning in the United States

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We determine appropriate earthquake early warning (EEW) alert threshold strategies that optimize alert performance for different shaking intensity targets for ShakeAlert, the earthquake early warning system for the West Coast of the United States. The current approach for determining which regions are issued EEW alerts in the ShakeAlert system does not account for ground-motion variabilities, so alert regions based on the estimated extent of target-level shaking will not alert all locations that end up experiencing target shaking, resulting in missed alerts at these locations. One method of reducing these missed alerts is to select the level of shaking used to issue an alert (the alert threshold) at a lower amplitude than the level of shaking targeted for warning (the target threshold). This expands the alert region and enables warnings to locations that experience larger-than-expected ground motions; however, this also increases the number of precautionary alerts issued to locations that experience smaller-than-target shaking amplitudes. We determine alert thresholds that optimize this tradeoff for target thresholds of modified Mercalli intensity (MMI) 4.0-6.0 using a ShakeMap catalog of 143 M5.0-7.3 U.S. West Coast earthquakes as ground truth, where we evaluate the quality of each alert threshold strategy in terms of both area and population as well as by expected warning times. Optimal alert thresholds produce alert regions that minimize missed alerts at target shaking levels while keeping precautionary alerts to locations that experience felt shaking, as precautionary alerts are perceived favorably over missed alerts. When earthquake source parameters are estimated accurately in ShakeAlert, we find the MMI 3.5 alert threshold is preferred for targets of damaging shaking (MMI 4.5+). Finally, our analysis presents a quantitative framework ShakeAlert operators can use to communicate EEW alerting strategies and performance expectations to users of the EEW system.

Low-latency Digitization, Communication and Alerting for Earthquake Early Warning Systems: Güralp Minimus

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Earthquake Early Warning Systems (EEWS) must combine low latency digitization, communication and computational processes to be effective. This maximizes the time between the characterization of an event and the warning of the population, thereby providing the longest warning time. Güralp Systems Ltd. (GSL) has developed the Minimus digitizer with a range of smart features that reduces latency to 40ms from signal input to digital output.

Minimus makes use of standard processing techniques such as causal FIR filters to reduce the digitization delay. GSL has also developed and equipped Minimus with the proprietary GDI-link streaming protocol to further reduce the delays in data communication. GDI-link streams data sample-by-sample and will dynamically adjust to the available bandwidth, therefore providing a fast and reliable communication protocol compared to traditional packetization protocols. This results in the transmitted data having a dramatically lower mean latency.

Minimus combines familiar STA/LTA algorithms with simple machine-readable event messages to alert operators and populations to impending ground shaking. When in a triggered state, the Minimus will instantly send a Common Alert Protocol (CAP) event message to a designated receiver containing the station metadata that indicates an event has occurred. The Minimus will locally compute the PGA, PGV and PGD parameters from the triggered event and will subsequently send these calculations as a secondary CAP message. CAP messaging makes use of existing internet infrastructure

and is already widely used in public communications which will aid EEW network operators with regards to implementation.

The Minimus has been designed as either a standalone digitizer or can be integrated into the Fortimus accelerometer and the Certimus broadband seismometer. The integrated systems provide compact and easy to deploy systems that are suitable for widescale EEW deployments.

MyShake + ShakeAlert: Using Smartphone Seismic Data for Earthquake Early Warning

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MyShake is a citizen science smartphone application which uses an algorithm to filter anthropogenic noise and detect earthquake onsets using the phones' onboard accelerometer. ShakeAlert is the US Earthquake Early Warning (EEW) system built on a dispersed network of permanent seismic stations that feed real-time data to detection algorithms. The goal of our research is to assess the potential of MyShake to augment the speed and accuracy of ShakeAlert's point source algorithm, EPIC, with a focus on the state of California where alerts have been publicly available the longest. Having been delivering alerts in California since October 2019, MyShake now has a substantial user base in the state, with roughly 220,000 active registrations (compared to the ~1000 ShakeAlert stations), with the densest clusters in urban areas.

We compare the detection capabilities of MyShake's triggering method and EPIC in combination and independently, using real data collected by both systems in earthquakes since October 2019. On an event-by-event basis, we assess whether incorporating MyShake data into the ShakeAlert system could have sped up detection and/or improved initial estimates of location, size and magnitude. For older events, we retroactively combine datasets. Beginning in June, 2021, real-time test versions of the EPIC algorithm have digested both data streams as they come in, providing realistic assessments of real-time performance. Preliminary results find that MyShake triggers can arrive at a server a full second earlier than the first ShakeAlert triggers, and can speed event creation by up to half a second without compromising the quality of the initial estimates. We also explore the efficacy of different algorithm approaches to incorporating MyShake data to best improve ShakeAlert performance.

Performance and Effectiveness of Earthquake Early Warning in Mitigating Seismic Risk

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We develop a framework to evaluate the performance and effectiveness of Earthquake Early Warning (EEW) systems in mitigating seismic risk. First, we determine warning time statistics by loss severity to assess the rate and consistency with which an EEW system could deliver timely alerts. Then, we develop a Genetic Algorithm approach to optimize an existing sensor network by proposing sites for new stations in order to enhance its EEW performance in damaging earthquakes. Finally, we assess the plausible EEW-related reduction in losses (here: casualties). This is done by means of a logical framework based on literature-informed assumptions. Risk estimates can then be recalculated assuming EEW system operation and compared to the initial values. We demonstrate our framework for Switzerland using 2,000 realizations of a 50-year-long stochastic earthquake catalog, which samples the earthquake rate forecast of the Swiss Hazard Model in space and time. For each of the almost 24k earthquake scenario ruptures ($5.0 \leq M \leq 7.4$), we predict shaking intensities and casualties at the largest Swiss cities. We find that the current Swiss Seismic Network could provide positive warning times to affected sites for about 80% of very damaging earthquakes (≥100 fatalities), and for around 85% of earthquakes with ≥10 fatalities. Warning times of >5s could be achieved for about 40-55% of very damaging earthquakes, and >10s for about 35%. A preliminary assessment suggests that an EEW system in Switzerland has the potential to reduce average annual fatalities and injuries by ~1-8% and ~3-16%, respectively, depending on the selected target city. However, since the number of earthquake casualties expected in Switzerland is overall low, using EEW to trigger automated actions could result in larger benefits.

Qube Network: A Low-cost Consumer Seismic Network for Earthquake Monitoring and Earthquake Early Warning

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The Qube is a low-cost Internet-of-Things (IoT) device for earthquake early warning (EEW). Each Qube costs less than $100, is about the size of a Rubik's cube, and has WiFi access. It detects vertical ground motion with a geophone at 100 sps and provides on-site warning through sounding the built-in alarm and regional warning through text messages. From September 2020 to December 2021, the Qube has detected all earthquakes over the magnitude M3.0 around Los Angeles, small nearby earthquakes down to M1.1 and large distant ones such as the M7.5 earthquake in Peru. An empirical formula is developed to estimate the magnitudes of local earthquakes using data for each stand-alone Qube.

A Qube Network has been under development to test the concept of a low-cost consumer-based earthquake monitoring and early warning network. As of January 1, 2022, six Qubes have been built and shipped to selected consumers' homes distributed throughout the Los Angeles metro area. The devices are installed by the consumers in a simple plug-n-play way and can resume all functions when connected or reconnected to power. Through a secure Amazon Web Services (AWS) IoT cloud platform, the six Qubes are remotely monitored and accessible for data transfer and software updates. Data is also automatically uploaded to Google Drive daily. The Qubes are time synced with a Caltech NTP server. Live communication among the devices, based on the MQTT protocol, is used to communicate detected events, in order to provide regional warning and to reduce false alarms from a single device. The Qube Network has detected multiple earthquakes and issued EEW alerts. The data from multiple Qubes is used to estimate the epicenter location and origin time after the earthquake, and additional work is being done to enable live calculations. The Qube Network has great potential in low-cost EEW and educational applications.

ShakeAlert Past Present and Future: Analysis of ShakeAlert's Time-to-alert Using the BDSN

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In the early stages of the ShakeAlert earthquake early warning (EEW) system, time-to-alert was highly dependent upon the network station coverage. As ShakeAlert has rolled out West Coast wide, roughly 75 percent of the seismic stations have been installed and are currently contributing to ShakeAlert. We analyze the impact of station density as the network has been built out using time-to-alert as a proxy for the health of the system using magD (https://github.com/pnsn/magd_client). As ShakeAlert converges on full buildout, we examine the impact of different current and planned telemetry upgrades to assess the impact of changes in connectivity to the time-to-alert.

Previous studies have demonstrated that with the addition of new seismic stations in strategic locations of Northern California, the time-to-alert increased significantly between May to September 2019 improved the time-to-alert and was part of the justification for the ShakeAlert's public rollout in October 2019 (Biasi and Stubailo, 2020).

Network coverage has improved considerably in the last two years, and we take this analysis a step further by looking at the impact of different telemetry types on the time-to-alert. ShakeAlert's teltmery is designed to avoid clusters of telemetry similarities. Impact of recent firestorms, rolling backouts and other hiccups in the connectivity framework there is a need to study these impacts. We look at timpact on he time-to-alert based upon the following questions; a) does a station's strategic location matter is stations with cell and radio connection are removed; b) can we predict system impacts if stations are moved from one form of connectivity, to the PSC microwave system; c) can we use time-to-alert as a proxy to determine if potential upgrades from outside contributors like CENIC will have a large impact; and d) what are the potential efficiencies that are gained by upgrading strategic stations to dual telemetry paths.

ShakeAlert network infrastructure is almost complete. Examining and upgrading points of failure in the telemetry paths is the next goal optimize the system and provide the best time-to-alert.

Testing the Finite-fault Rupture Detector (FinDer) in New Zealand

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Rapid information on fault rupture extent is important to estimate seismic ground-motions and damage from large earthquakes. The Finite-Fault Rupture Detector (FinDer) algorithm computes rapid line-source models from template matching that characterize the spatial extents of high-frequency seismic ground-motions around the evolving fault rupture. FinDer was originally developed for earthquake early warning (EEW) and is currently adopted by the United States West Coast ShakeAlert EEW system. FinDer line-source models have, however, also proved valuable for providing rapid information on source dimensions critically needed for ground-motion maps and earthquake loss estimates. Supporting different widely-used seismic monitoring platforms (Earthworm-AQMS, SeisComP) makes it possible to run and test FinDer in various seismic networks and tectonic settings around the world, both in real-time (e.g., US West Coast, Central America, Chile and Switzerland), and offline (e.g., Central Italy, Japan and China). Here we report on the FinDer off-line performance in New Zealand using seismic waveform archive playbacks, or time-independent ground-motion maps of recent major large earthquakes. Motivated by its promising performance, even in complex earthquakes like the M7.8 Kaikoura multi-rupture event, we have started to set-up a SeisComP system to compute FinDer models in real-time for on- and off-shore seismicity in New Zealand. The resulting models are intended to support the generation of rapid response information and may be integrated into national ShakeMaps in the future.

Testing the Latency and Geofence of Wireless Emergency Alerts Intended for the ShakeAlert® Earthquake Early Earning System, West Coast, USA

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ShakeAlert, the United States Geological Survey-managed earthquake early warning system for the West Coast of the United States, provides crucial warnings before strong shaking occurs. The Federal Emergency Management Agency (FEMA) uses the Integrated Public Alert & Warning System (IPAWS) gateway as an alerting platform with Wireless Emergency Alerts (WEAs) informing people via their smartphones and other mobile devices about various events, such as natural hazards or child abductions, in their geographic location. However, little is known about the IPAWS latency. Given that people may have only a few seconds of notice when they receive a ShakeAlert Message, quantifying WEA latencies is critical to understanding whether the IPAWS system is useful for EEW.

In this study, we tested the WEA distribution system's performance, both with devices in a controlled environment and with a 2019 community-based survey in the City of Oakland and San Diego County, California. The controlled environment test used smartphones and associated devices to determine alert receipt times; the community survey had participants self-report their receipt times. By triangulating the data between the controlled test environment and the community surveys, we determined the latency and whether the geofence (the geographic area where the alert was intended to be sent) held broadly. We found that the latencies were similar between the two tests despite the large difference in population sizes. WEA messages were received within a median time frame of 6-12 s, and the geofence held with only a few exceptions. We use this latency to assess how the system would have performed in two large earthquakes, the 1989 M6.9 Loma Prieta and 2019 M7.1 Ridgecrest earthquakes, which both occurred in California near our WEA test locations. Our analysis revealed that had IPAWS been available during those earthquakes, it would have provided crucial seconds of notice that earthquake shaking was imminent.

The Potential for Small-world Phenomena in Ground Motion-based Earthquake Early Warning

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Complex networks in the real-world, such as social networks, the power grid and transportation systems, are often represented by "graph" data structures, which consist of a set of "nodes" and links between nodes to connect them together. These graphs often exhibit so-called "small-world" effects, where a node in the network's underlying connectivity graph is highly connected to its nearest neighbors, yet only a few connections away from all nodes in the network through its "friends of friends". Two features–local clustering and short global paths–in small-world graphs allow for efficient signal propagation at both local and global scales (Strogatz, 2001).

Reimagining a seismic network as a small-world graph, with stations as nodes, offers the potential for increased alert speed in Earthquake Early Warning (EEW). We build off the Propagation of Locally Undamped Ground Motion (PLUM - Kodera, 2018) approach to EEW, which limits alerts to regions within a fixed distance R from any seismic station that records ground motion above a set shaking threshold. We modify PLUM to also send alerts to a small number of random locations, on the order of 0.1 to 1% of the total stations, beyond a distance R. Using the 1804 stations in the LArge-n Seismic Survey in Oklahoma (LASSO) network (Dougherty, 2019), we show that, due to shortcut connections between faraway stations, adding small-world effects to the PLUM algorithm greatly reduces the time required to send an alert across the network. We suggest that our small-world version of PLUM offers potential for graph-based deep learning approaches to EEW in the future.

Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy

Oral Session · Friday 22 April · 2:00 PM Pacific

Conveners: Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Chris Milliner, Caltech (milliner@caltech.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Austin Elliott, U.S. Geological Survey (ajelliott@usgs.gov); Jessica A. T. Jobe, U.S. Geological Survey (jjobe@usgs.gov)

Distributed Faulting and Off-fault Deformation Revealed by Optical Image Correlation Using Unmanned Aerial Vehicle Imagery of the 2019 Ridgecrest Earthquake Sequence

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Unmanned aerial vehicle (UAV) imagery of the 2019 Ridgecrest earthquake sequence — including sections of the M6.4 and M7.1 rupture — reveals a principal fault and many secondary distributed faults within tens of meters of the main rupture. Whether these distributed features accommodate coseismic displacement or result from ground shaking in this event has not been established. Distributed faulting is often difficult to measure in the field and is not visible in satellite imagery (>0.5-m-resolution) used in optical correlation studies. We use optical pixel correlation with 0.01-0.02-m-resolution UAV imagery and pre-event 0.6 m-resolution aerial imagery from the National Agriculture Imagery Program (NAIP) to measure 160 fault-parallel, coseismic displacement estimates. The results capture 1.6 km of the M6.4 and 7 km of the M7.1 surface ruptures. We use COSI-Corr for image cross-correlation, which allows for sub-pixel correlation with a detection limit of 0.06 m of displacement. Our displacement estimates are similar to satellite imagery correlation displacement estimates from prior studies and are generally larger than field-based measurements. Similar to other correlation studies, our larger displacement results compared to field measurements are attributed to distributed faulting and off- fault deformation, which may go unnoticed during field surveys. At one site along the M6.4 surface rupture, only 43% of the coseismic displacement was measured in the field, indicating that deformation on secondary faults and off-fault deformation is difficult to fully capture with field measurements alone. The results from this study have implications for seismic and fault displacement hazard assessments that rely on measurements and data from a single fault strand, suggesting that the total deformation may be underestimated if distributed faulting and off-fault deformation are not considered.

Deep Coseismic Slip in the Cascadia Megathrust Can Be Consistent with Coastal Subsidence

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At subduction zones, the down-dip limit of slip represents how deep an earthquake can rupture. For hazards it is important—it controls the intensity of shaking and the pattern of coseismic uplift and subsidence. In the Cascadia Subduction Zone, because no large magnitude events have been observed in instrumental times, the limit is inferred from geological estimates of coastal subsidence during previous earthquakes; it is typically assumed to coincide approximately with the coastline. This is at odds with geodetic coupling models, it leaves residual slip deficits unaccommodated on a large swath of the megathrust. Here we will show that ruptures can penetrate deeper into the megathrust and still produce coastal subsidence provided slip decreases with depth. We will discuss the impacts of this on expected shaking intensities.

Interseismic Deformation in the Dead Sea Fault Region Inferred by InSAR and GNSS Measurements

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The Dead Sea Fault (DSF) is a N-S transform plate boundary between the Sinai subplate and the Arabian plate. The relative left lateral motion across the DSF has been estimated to be 3-7 mm/year, with varying slip rates on different segments of the fault. The Carmel Fault System (CFS) within the Sinai subplate consists of NW-SE trending faults and extends from the central part of the Jordan Valley, just north of the Dead Sea, to the Mediterranean Sea. Both extensional and left lateral motion was identified along the CFS with sub-millimeter slip rates.

Several studies have used GNSS and geological data to explore the tectonic region around the Dead Sea. Over the last decade, InSAR has become a common practice for different crustal deformation studies with increasing data availability and open source programs that facilitate the analysis of time series and two-scene interferograms. While GNSS has a better temporal resolution of mostly 24-hour sampling (1 Hz for high-rate) and a sparse temporal coverage, InSAR covers larger areas but with a repeating period of ~6 days. Furthermore, specifically for the DSF region, InSAR has the ability to measure deformation along the eastern part of the fault where GNSS coverage is limited. By combining both measurements one can benefit from the GNSS temporal resolution and InSAR spatial resolution, having a better view of the study area and learn about short- and long-term processes.

Here we show preliminary results of velocity field and strain rates along the DSF and CFS inferred by GNSS and InSAR measurements. The objectives are (1) to resolve the accumulated strain and varying slip rates in different sections of the fault, (2) examine low seismicity sections such as Wadi Arava, creeping sections, locked sections and their locking depths, (3) explore the spatial extent of the CFS together with its faulting style (transverse versus extensional) and slip rate accommodation. These tasks aim to increase our knowledge about the region's seismic hazard assessment.

Earthquake Behaviors in Earthquake Cycle Simulations With Fault Damage Zones

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Faults are usually surrounded by damage zones associated with localized deformation. Here we use fully dynamic earthquake cycle simulations to quantify the behaviors of earthquakes in fault damage zones. We show that fault damage zones can make a significant contribution to the spatial and temporal seismicity distribution. Fault stress heterogeneities generated by fault zone waves persist over multiple earthquake cycles that, in turn, produce small earthquakes that are absent in homogeneous simulations with the same friction conditions. Shallow fault zones can produce a bimodal depth distribution of earthquakes with clustering of seismicity at both shallower and deeper depths. Fault zone healing during the interseismic period also promotes the penetration of aseismic slip into the locked region and reduces the sizes of fault asperities that host earthquakes. Hence, small and moderate subsurface earthquakes with irregular recurrence intervals are commonly observed in immature fault zone simulations with interseismic healing. To link our simulation results to geological observations, we will use simulated fault slip at different depths to infer the timing and recurrence intervals of earthquakes and discuss how such measurements can affect our understanding of earthquake behaviors. We will also show that the maturity and material properties of fault damage zones have strong influence on whether long-term earthquake characteristics are represented by single events.

Juicy Data — Preliminary Results From a Drone Lidar System Applied to Tectonic Geomorphology

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Over the last two decades, the proliferation of lidar has led to many advances in our understanding of surface rupturing faults. Much of this data has been collected using crewed airborne laser scanning (ALS) systems. More recently, Structure-from-Motion (SfM) from consumer uncrewed aerial vehicles (UAVs) has become a common tool for field geologists. As of yet, UAVs equipped with lidar have not been widely applied to tectonic geomorphology. Here, we present results from our newly built UAV laser scanning (ULS) system with specific application towards studying fault-related surface topography. The platform, a Riegl MiniVux 1-UAV laser scanner mounted to a DJI M600 Pro drone, provides a unique, cost-effective way to collect lidar datasets, necessary for studying tectonic geomorphology in highly vegetated regions such as the Pacific Northwest. While this platform can be used to collect lidar data in areas without previous coverage, it can also improve the resolution for areas where there is pre-existing coverage and, in the event of a large earthquake, it could also be used collect post-event lidar. We have used this platform to collect several datasets over faults located in a variety of terrain types and vegetation in Western Canada. To validate the quality of our ULS data, we provide comparisons to established methods of collecting high-resolution topography, including conventional ALS and SfM products. The platform offers a marked increase in point density (~40 pts/m^2) and canopy penetration over conventional ALS (~10-15 pts/m^2), due to lower flight altitude and slower acquisition speeds. Higher resolution topography allows fine-scale features, such as small channel offsets, glacial scouring and secondary faulting, to be better resolved. However, the platform does suffer from practical and regulatory constraints that limit the area covered in a single day to ~2 km^2. We propose several improvements that will address these limitations.

Strawberry Mountains Slip Rates in Suspiciously Seismically Still Eastern Oregon

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Lidar topographic data for the Strawberry Mountains, Oregon has revealed youthful fault scarps that likely result from Holocene-age earthquakes. We have mapped scarps striking roughly east-west across the northern foothills of the Strawberry Mountains (Strawberry Mountains Fault, SMF) and along another lineament striking south along the uppermost John Day River 10 km to the south. SMF scarps are aligned with the bedrock John Day Fault, a reactivated Miocene structure that is accommodating distributed extension north of the Basin and Range region. The Strawberry Mountains sit near the nexus of the Basin and Range province to the south and the tectonically stable Blue Mountains province to the north. We constrained Quaternary slip rates on the SMF with ^{3}He cosmogenic radionuclide (CRN) dating of glacial features. During the Last Glacial Maximum (LGM), the Strawberry Mountains contained numerous alpine glaciers which deposited prominent lateral and recessional moraines. The SMF offsets these moraines between 1 and 3 m. Preliminary analysis of CRN data shows these glacial features to be LGM-aged with a peak at ~23.6 ka. When combined with measured offsets, the slip rate of the SMF is 0.1 – 0.2 mm/yr in the Holocene.

A dense paleoseismic coring transect was collected across the SMF in a basin impounded by an uphill-facing scarp above a glacial valley. It records evidence for two surface-rupturing events since the LGM, and vertical separation of 3.1 meters. ^{14}C dates from onlapping stratigraphy and surface-rupture-correlative colluvium are pending. This study represents the first study of a Quaternary surface-rupturing fault as well as the first absolute CRN data within a 140-km radius in Eastern Oregon. Data from this study will fill large gaps in knowledge of seismic hazard in Eastern Oregon and give insight to the Pleistocene and Holocene behavior of the recently discovered SMF.

Continued Building of STEPS: Slip Time Earthquake Path Simulations

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Geologic slip rates are models of time-averaged measurements of on-fault coseismic displacement. However, long-term slip rates (e.g., > 10,000 years) may not be representative of short-term fault behavior (e.g., < 100 years), which is of particular interest for seismic hazard analyses. Here, we explore hypothetical use cases of the Slip Time Earthquake Path Simulations (STEPS) numerical methodology, which creates earthquake paths between geologic observation points, to compare the relative importance of different types of field-derived data within the STEPS code. We investigate the relative influence of paleoearthquake chronologies (including time since last event) and dated offset feature(s) in determining the relative probability of earthquakes occurring in any 50-yr time interval (i.e., earthquake rates). Additionally, we examine the influence of inherent biases in displacement–time observations themselves (ex: temporal lag between when the feature was formed/deposited and the earthquake that displaced that feature). We revise the STEPS approach to solve for earthquake rates, both in the past and in the future. Additionally, because earthquake paths are now constructed via event interpolations between observation points in displacement–time space, we can estimate maximum earthquake path variability between points. Preliminary results indicate that knowledge of paleoearthquake chronologies, particularly knowledge of the most recent event, guide the earthquake paths near the origin of displacement–time space (i.e., present day) by providing the critical constraint of the time since last event. That said, long-term dated offsets or basic slip rate estimates provide a necessary limit on path construction at the older end of the record. Combined, these data provide estimates of geologically derived earthquake rates that can then be compared to other estimates of earthquake rates (e.g., physics-based rupture simulators).

The Mechanics and Frequency of Joint Earthquake Ruptures of the San Andreas and San Jacinto Faults

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Large, multi-fault earthquakes increase the threat of strong ground shaking and reshape the probability of future events across a system of faults. Fault junctions act as conditional barriers, or earthquake gates, that stop most earthquakes but permit junction-spanning events when stress conditions are favorable. Constraining the physical conditions that favor multi-fault earthquakes requires information on the frequency of isolated events versus events that activate faults through the junction. Measuring this frequency is challenging because dating uncertainties limit correlation of paleoseismic events at different faults, requiring a direct approach to measuring rupture through an earthquake gate. We show through documentation and finite element modeling of secondary fault slip that co-rupture of the San Andreas and San Jacinto faults through the Cajon Pass earthquake gate occurred at least three times in the past 2000 years, most recently in the historic 1812 earthquake. Our models show that gate-breaching events taper steeply and halt abruptly as they transfer slip between faults. Comparison to independent chronologies shows that 20-23% of earthquakes on the San Andreas and the San Jacinto faults are co-ruptures through Cajon Pass.

Constraining a Long History of Paleolake and Paleoearthquake Activities Using Deep Boreholes at the Ancient Lake Cahuilla, Coachella, California

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Constraining the long-term sedimentary history and stratigraphy of the ancient Lake Cahuilla (LC) is crucial to constructing the long-term paleoearthquake activities on the southernmost San Andreas Fault (SSAF). Recent paleoseismic investigations along the 100-km SSAF suggest an average recurrence interval of the last seven major rupture events (~1–0.3 ka) ranging between ~116 and ~221 yr. Yet, the most recent earthquake along this portion of the SSAF occurred ~300 yr ago, around the same time as the last filling of LC. Some researchers have proposed that the lake levels of the ancient LC affect the regional stress field and that particular stages of lake filling events correlate to earthquake occurrence. However, this hypothesis is debated, in part due to limited trench records that only extend to <2 ka and due to disagreement on how to define a lake filling event from stratigraphic evidence in a shoreline environment. To resolve this question, a detailed investigation of a long depositional record with high-resolution age constraints is required. We drilled two continuous boreholes, 33.5 and 40 m deep, from the Coachella paleoseismic site along the SSAF. We extracted the 33.5-m-deep core within the Coachella structural depression (CSD). The 40-m core was extracted near the Mesquite Dune (MD), ~135 m southwest of the CSD core outside the deformation zone. Both cores likely record ~19 lake highstands. We analyzed 13 and five single-grain luminescence samples from the CSD and MD cores, respectively, and ten ^{14}C ages from the CSD core. Our ages from the cores extend the lake level history back to ~7 ka. The ages from the CSD core suggest that the average interval between the lake highstands is ~0.2–0.3 ka, and the average sedimentation rate is ~5±0.3 mm/yr over the past ~7 ka. Our work provides the longest history of LC's lake cycles, timing and recurrence cluster of multiple earthquake cycles along the SSAF and periods of sediment deposition and hiatuses in the region—the key parameters to assess the regional seismic hazards.

Do Earthquakes Rupture Through Releasing Bends in the Western Nepal Fault System?

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Knowledge of potential seismic sources in the upper-plate of Western Nepal is limited. Recent studies of the Western Nepal Fault System (WNFS), an oblique-dextral-slip system of splay faults, expand the known fault geometry and segmentation based on the mapping of the tectonic geomorphology and documentation of offset landforms. The WNFS trends along the northern bifurcation (PT2-N) of the physiographic transition between the Lesser and the Greater Himalaya (PT2). It contains a large, greater than 100 km wide, right-stepover between the primary NW-SE-oriented Talphi-Tripurakot fault segments and the Bari Gad fault. These segments are connected by ~N-S oriented faults, such as the Jang la Oblique and the Dhorpatan fault segments. To investigate the rupture extents of large, surface-rupturing earthquakes, we seek to characterize the earthquake history of the WNFS. We conducted paleoseismic investigations at three sites on the fault system in Fall 2021. The three trenches dug revealed previously undocumented earthquakes and begin to help establish whether ruptures on this fault system are not hindered by bends in the fault traces. At Puphal Phedi at least four events were exposed in each trench, five events were exposed at our Naya Ban trench and at Bhujekhung, at least two were exposed. Previous results from the trenches dug in 2019 also

demonstrate the occurrence of multiple Late Holocene earthquakes. Overall, our results provide important constraints for seismic hazards which we will implement into regional seismic hazard models. This will improve risk mitigation and resilience development in the High Himalayas of Western Nepal as well as inform models of the connectivity between ruptures of the Main Frontal Thrust and the WNFS.

Advances in Earthquake Geology: Spatiotemporal Variations in Fault Behavior From Geology and Geodesy

Poster Session · Friday 22 April · Conveners: Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Chris Milliner, Caltech (milliner@caltech.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Austin Elliott, U.S. Geological Survey (ajelliott@usgs.gov); Jessica A. T. Jobe, U.S. Geological Survey (jjobe@usgs.gov)

Constraining the Uplift History of the Montezuma Hills, Sacramento Delta Region, California

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The Montezuma Hills are an area of broad relief reaching ~90 m elevation amid the mostly flat sea-level landscape of the Sacramento Delta. Their plateau-like geomorphology suggests a relict surface that has been uplifted and tilted northward. This deformation would be related to the Great Valley fault system which runs along the east side of the California Coast Ranges, but the precise causative structure(s) remain unidentified. Little is known about faults in the area other than crude locations of a few; slip rates, earthquake frequency, geometry and connectivity are unknown. Improving knowledge of these faults is vital both for understanding the local tectonics and for clarifying the hazards posed to the Delta region.

We approach this problem by investigating the uplift history of the Montezuma Hills. The hills are capped by the near-horizontal Montezuma Formation, largely composed of fine-grained sediments that are presumed to be deltaic deposits. This formation is generally identified as early Pleistocene, but the only quantitative age constraint comes from the 3.3 Ma Putah Tuff in the underlying Tehama Fm., giving an uplift rate of >0.03 mm/yr. We have identified a series of wind gaps (former distributary channels of the Delta) that indicate a locus of uplift along the western crest of the hills. We excavated a series of pits in and near these wind gaps, all of which revealed similar massive silt deposits below modern soil. The similarity of the sediment inside and outside the wind gaps suggests that it is all part of the Montezuma Fm. which was deposited prior to the incision of the channels and that no sediments associated with channel flow are preserved in the wind gaps. We are in the process of luminescence dating which will at least place a lower bound on the age of the deposits. If our samples prove too old for luminescence ages, we will pursue other techniques such as analysis of microfossils or pedogenic carbonate. Establishing an age for the Montezuma Fm. will greatly refine the uplift rate of the Montezuma Hills.

Do Terrestrial Lidar Data Improve Understanding of Fault Offsets From the 2019 Ridgecrest Earthquake?

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The July 5th, 2019 M7.1 Ridgecrest, CA earthquake caused extensive right-lateral surface rupture. Natural and cultural features were used during field response to measure offsets using traditional methods. Multiple field teams independently measured the offsets, leading to a range of offset measurements and corresponding uncertainties. We collected terrestrial laser scanner (TLS) data at six sites to evaluate if capturing 3D microtopography at the highest possible resolution allows us to more accurately measure fault slip and reduce measurement uncertainty compared to traditional field measurements. The six sites were located on a playa where the rupture offset stream channels and tire tracks. TLS scans capture subtle features and microtopography that may otherwise go unnoticed in the field due to vegetation, lighting or other factors. We measured geomorphic offsets on the ultra-high-resolution topographic data manually and with a semi-automatic offset measurement tool (LaDiCaoz). With LaDiCaoz, offset measurements agreed with field measurements best when the fault zone is narrow and the offset feature is a stream channel. For example, at site 4 LaDiCaoz indicated a 4.5±0.25 m offset, which is consistent with the field measurement of 4.47±0.24 m (DuRoss, 2019). However, TLS-derived LaDiCaoz and manual measurements at sites featuring offset tire tracks and wider fault zones were sometimes inconsistent with field measurements. At the Midas site, manual measurement of an offset tire track from lidar showed an offset of 3.11±0.5 m, which differs from the field measurement of 4.15±0.45 m (DuRoss, 2019). This shows how fault width may affect the consistency of results, as the fault zone width at Midas was nearly 7 m, compared to less than 1 m at Site 4. Overall, TLS surveys proved to be a very valuable tool for visualization of the fault rupture at every site. However, as is likely the case with field measurements, uncertainty may increase as the fault zone widens.

Evidence for Substantial Dip Slip on the Fastest Ocean-continent Transform Plate Boundary: Repeated Coseismic Uplift on the Fairweather Fault, Southeast Alaska

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Oblique convergence along the Yakutat-(Pacific)-North America plate boundary drives extreme rock uplift along Earth's fastest slipping (≥49 mm/yr) ocean-continent transform fault, the Fairweather fault. The 1958 M_w 7.8 Fairweather earthquake featured 3.5–6.5 m of right-lateral displacement and, at one site, ~1 m vertical slip. For most of the surface rupture, vertical slip was too little to detect. Intriguingly, this was the case at Icy Point, where the near-vertical Fairweather fault focuses extreme rock uplift and rapid lateral slip by accommodating both convergent and fault-parallel strain during independent dip-slip and strike-slip events. We use 1.0 m resolution digital elevation models to map active faults, uplifted marine and fluvial terraces, and document past convergent earthquakes with 3–5 m of coseismic uplift per event—a mode of deformation not observed in 1958. Radiocarbon and luminescence dating provide timing to estimate 4.6–8.9 mm/yr Holocene surface uplift rates, which match 5–10 km/Myr middle Pleistocene rock uplift rates estimated from thermochronometry. Dip slip earthquakes relieve convergent strain partitioned onto reverse faults that form a 10-km-wide, asymmetric, positive flower structure along a 20°, ~30-km-long restraining double bend in the Fairweather fault. The principal reverse fault in the flower structure is the offshore Lituya Bay-Icy Point fault, which ruptures on average every 500–1175 years evident from uplifted Holocene marine terraces. Simple reverse-fault geometries imply 3.5–10 m slip per event in earthquakes of M_w 7.0–7.5, based on earthquake scaling relationships. Substantial vertical slip also occurs on the Fairweather fault where it offsets stream terraces by >25 m, its strike diverges >20° away from plate boundary motion, the fault juxtaposes near-surface rocks of different strength, and where the plate-boundary stress state may vary in time due to the oblique collision between the Yakutat block and North America.

Examining Tectonically Offset Geomorphic Features Using Aerial Imagery and Field Mapping to Estimate Slip Distribution and Slip-per-event for Paleoearthquakes Along the Southernmost San Andreas Fault

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To obtain an estimate of the slip distribution and slip-per-event for past earthquakes on the southernmost San Andreas Fault (sSAF) in the Salton Trough, we measured tectonically offset geomorphic features along approximately 85 km between Bombay Beach and Indio Hills. In addition to utilizing topographic data from B4 light detection and ranging (lidar) and Structure-from-Motion (SfM) imagery, we constructed new high-resolution orthomosaics and digital surface models (DSMs) generated from Structure-from-Motion-Multiview Stereo (SfM-MVS) techniques from uncrewed aerial vehicle (UAV) imagery at Durmid Hill, Salt Creek, Ferrum and Indio Hills. The aerial imagery, along with field mapping, were used to identify and measure over 130 offset features with lateral displacements ranging between 2 to 23 m. Offset features displaying less than ~1 m of lateral displacement were not considered in our study as these features likely reflect modern creep and triggered slip events, which post-date the most recent surface-rupturing event in ca. 1726 AD. Our results show that the last several large, surface rupturing events produced offsets with average displacements of 2.5-4.0 m per event; historically, as much as ~15% of the offset results from interseismic creep. We note that lower overall lateral slip values are measured where multiple fault strands are present. We combine these observations with paleoearthquake event dating to explore limits of the size and extent of past ruptures and the connectivity between neighboring faults and other strands of the sSAF.

HDBSCAN Cluster Analysis of Legacy Earthquake Surface Rupture Datasets

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Over the past three decades, we have amassed a wealth of earthquake surface rupture maps of increasing resolution. These datasets contain an abundance of untapped information. We used HDBSCAN cluster analysis to find commonalities between four major surface-rupturing earthquakes in the Eastern California Shear Zone and northern Mexico: Ridgecrest (2019), El Mayor-Cucapah (2010), Hector Mine (1999) and Landers (1992). To compare surface rupture characteristics, we extracted four features from these maps: mean and variance of fracture density, relative orientation between fractures and the principal rupture and the length of each fracture. We found that density was the most impactful feature across all earthquakes and minimum cluster size should be roughly 10% of the total data size. Although no positional data was included in the clustering, clusters tended to localize geographically. Each cluster was characterized by a distinct deformation signature, including sections of localized rupture, widely distributed deformation and secondary deformation features. Through clustering, we aim to find connections between legacy datasets, to distinguish primary and secondary deformation and to unveil the connection between surface rupture styles and earthquake mechanics.

Hosgri Fault Zone-driven Uplift of the Irish Hills, Central Coastal California: Viscoelastic Crustal Deformation Modeling Results

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Most of the central California coast west of the San Andreas fault (SAF) has slowly uplifted over the past 120 kyr. The offshore Hosgri fault zone (HFZ) in central coastal California has a reverse slip component that produces coastal uplift. Correlated and dated 120 ka emergent marine terrace bedrock surface elevation measurements provide coastal uplift rate data used with viscoelastic crustal-mantle deformation modeling to test the hypothesis that reverse-oblique earthquakes on the HFZ explain post-120 kyr observed coastal uplift rates of up to 0.2–.25 m/kyr. Model inputs include elastic seismogenic upper crust, viscoelastic lower crustal and upper mantle and HFZ geometry based on published crustal-mantle viscoelastic structure. Viscoelastic deformation modeling calculations of long-term uplift rates use a two-segment HFZ geometry based on published fault mapping and slip rates within the range published for the HFZ. The modeling shows that the rate and pattern of uplift of the coast and Irish Hills can be solely attributed to transpressional deformation of the HFZ. It is not necessary to add onshore thrust-reverse faults to explain observed ≤120 kyr coastal uplift rates. Modeled HFZ deformation explains observed folded Quaternary sedimentary structures observed in bathymetric and seismic reflection data in the offshore HFZ step-over region and the location and amplitude of the deep-crustal Santa Maria anticline in the hangingwall of the southern HFZ. These results suggest that viscoelastic deformation modeling of the reverse-slip components of other steeply-dipping, predominantly strike-slip offshore-nearshore faults along the California coast may explain portions of observed post-120 ka California coastal uplift rates across the region.

How Reliable Is the Geomorphic Record of Multiple Strike-slip Earthquakes?

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Offset geomorphic features along strike-slip faults record on-fault evidence of past earthquakes. Lidar and imagery make it possible to map and measure many offsets to infer surface slip distribution and the number and size of prior earthquakes. These interpretations often assume that earthquakes have similar size offsets (characteristic slip) to assign measurements to individual events. However, slip in each earthquake is spatially variable and climate-modulated geomorphic change in the interseismic period modifies offset features. These factors erode confidence in slip distributions compiled for older earthquakes and highlight the need to probe these datasets further to ensure reliable interpretation. Here, we test the fidelity of the geomorphic record and the cumulative offset probability density (COPD) interpretation method with numerical models of multiple earthquakes under numerous diffusion and slip-rate parameter values compared to offset measurements from 24 strike-slip faults with multiple paleo-earthquakes and associated climate data. We find that the geomorphic expression of repeated strike-slip surface ruptures is affected by: (1) relative rates of climatic and tectonic processes, (2) local topography, which affects drainage deflection along versus incision across a fault, (3) surface slip variability and (4) geomorphic change in the interseismic period. From modern earthquakes, we find that the most common offset values may not correlate to average slip, an assumption inherent to COPD interpretation. Though these factors can impede inference of a unique slip history, treating multiple-earthquake offset data with smoothing and 2-dimensional density models allows a more nuanced interpretation of paleo-slip distribution. We suggest considering regional climate data and multiple interpretation methods in constructing paleo-slip distributions and stress that multiple-earthquake slip histories made using the COPD method may be non-unique.

Investigating the Mechanics of Strain Partitioning at the Rakhine-Bangladesh Megathrust Using InSAR Time-series

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The Rakhine-Bangladesh megathrust extending from offshore Myanmar to central Bangladesh is accommodating active deformation between the Indian plate and the Burma micro-plate, at the eastern edge of the India-Eurasia collision zone. In this region, dextral-oblique collisional strain is partitioned across several tectonically active structures including the megathrust, the Indoburman Ranges (fold-and-thrust belt with additional potential strike-slip structures) and the dextral Sagaing Fault. The megathrust and Indoburman ranges have been historically under-studied compared to similarly active regions worldwide, owing in part to the region's dense vegetation and limited accessibility. The advent of remote geodetic observations such as L-band Interferometric Synthetic Aperture Radar (InSAR) has greatly improved our ability to map tectonic strain accumulation in such areas, even through dense vegetation. In this study, we seek to answer how strain is partitioned in the Indoburman Ranges using L-band InSAR. We use observations from ALOS-2 wide-swath imagery to perform InSAR time-series in the central Indoburman Ranges spanning Bangladesh, India, and Myanmar. The data are corrected for variable ionospheric and tropospheric delays using the split-spectrum method implemented in the ISCE software package from JPL and the GACOS atmospheric delay model. We use the resulting map of line-of-sight tectonic velocities to assess the pattern of interseismic strain across the central fold-and-thrust belt and construct a three-dimensional model of the active structures at depth.

Landslides as Paleoseismological Indicators: Experiences Using Geotechnical Back-analyses in the Andes

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Large volume landslides are often triggered by earthquakes in seismically active mountain regions. Recent examples in the central Andes and the usu-

ally clustered geographic distribution of older landslides suggest that the most likely source of coseismic rock slides and rock avalanches are shallow crustal earthquakes from nearby active faults. Using this as a working hypothesis, large volume, well preserved prehistoric landslides can be studied using geomorphological, engineering geological and geotechnical tools, including Newmark-type, limit equilibrium and numerical modelling back-analyses. We present recent and ongoing examples of studies in the Chilean and Argentinean slopes of the central Andes. Research in the Argentinean region of San Juan-Mendoza (31-33°S) allowed the development of a methodology to identify nearby faults as potential sources of earthquakes that may have induced the slope instabilities, combining the geotechnical analyses and ground motion prediction equations. This methodology is now being applied in similarly distributed megalandslides along the Pocuro fault zone in the Chilean side (32°-33°S). The coseismic nature of paleolandslides cannot be assured from geotechnical studies alone, as other factors such as post-glacial debutressing and climate may also induce large slope collapses in these mountain environments. However, the combination of geoengineering analyses with geochronological and neotectonic studies may provide useful information on the age and magnitude of ancient, large shallow crustal earthquakes, contributing to the characterization of seismic hazard in mountain regions.

This work is funded by ANID-Fondecyt 1201360 and 1200871 grants in Chile and by grants from ANLAC program (Res. 571/15), and the SeCTyP (Cod. A06/669; Res. 3820/2016) of National University of Cuyo and the Ministry of Defence (PIDEF 05/18) in Argentina.

Lidar Data Reveal New Faults in the Epicentral Region of the 2020 M 6.5 Stanley, Idaho Earthquake

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The March 2020 M6.5 Stanley earthquake occurred in central Idaho, within the northern Basin and Range Province. The earthquake is enigmatic as it occurred ~18 km north-northeast of the Holocene-active Sawtooth fault, plots in an area devoid of Quaternary active structures and yields focal mechanisms with north-south or east-west dominantly lateral slip rather than normal faulting. Aftershocks occur within a north-northwest-aligned zone that is dominantly in the footwall of the east-dipping Sawtooth fault. These observations indicate that seismogenic structures in central Idaho are more complex than current mapping suggests.

We use high-resolution (0.5 m) post-event lidar data as a basis for geomorphic mapping at the northern end of the Sawtooth fault and in the Stanley earthquake epicentral area. Our preliminary mapping reveals a complex northern Sawtooth fault, which extends at least 6 km farther north than previously mapped and includes a ~10-km-long northeastern splay. We also identified evidence for two unrecognized late Quaternary faults. The first is ~5 km west of the Sawtooth fault and expressed as a nearly continuous linear alignment of scarps for ~10 km. From south to north, the fault cuts late Quaternary alluvial-fan and glacial deposits and a broad valley floor, then crosses Cape Horn Creek, climbs topography and cross cuts major valleys before becoming indistinct in steep glaciated terrain. The second fault is ~8 km north of the newly mapped northern extension of the Sawtooth fault in a basin at the head of Shake Creek. The fault is at least 1.8 km and possibly 3 km long and expressed as a nearly continuous linear alignment of scarps that cross steep colluvium and striated late Pleistocene deglacial surfaces and deposits. Both faults strike north-northwest, dip west—opposite the Sawtooth fault—and have unclear relationships to the March 2020 M6.5 earthquake.

Marine Geomorphology Across the Seattle Fault Zone: Clues for One or More Ruptures Since Deglaciation

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New and legacy seismic reflection profiles offshore Seattle, Washington enable a provisional recount of large thrust earthquakes of postglacial age on the Seattle Fault Zone. The Seattle Fault Zone contains multiple reverse faults, including antithetic backthrusts, and extends eastward beneath the city of Seattle. Hazard estimates allow for a 5000-year recurrence interval for magnitude 7 earthquakes on a main blind thrust, including one large post-glacial earthquake, 900–930 CE, that has been inferred from the geologic record. Open-ended recurrence intervals at least twice this long have been estimated from present elevations of deltas built into a late-glacial lake (by Robert Thorson; doi: 10.1126/science.260.5109.825) and of bathymetric benches beneath Puget Sound (by Ralph Haugerud; doi: 10.1130/2017.0049(01)). The benches likely represent a relative sea level lowstand around 11,000 years ago. Haugerud found that its depth, which is around 50 m near Seattle, increases southward consistent with glacioisostatic rebound. But he also noted that the bench profile steps upward to the south across the Seattle Fault Zone, and that the height of the step, estimated as 8 m, is similar to the maximum vertical offset of shorelines displaced in 900–930 CE. We are looking beneath the benches with new and legacy seismic reflection profiles. The unpublished legacy data was collected by Mark Holmes (USGS) in 1982 with a minisparker, and the new data we collected in 2019 with higher-frequency CHIRP. The results thus far focus on two of the submerged benches offshore Seattle. The inner edges of these benches appear to be draped in sediment. Using back edges beneath the drape, we estimate an offset of 11 m across the fault. This amount would be consistent with either two large earthquakes or more complicated deformation during one large earthquake and multiple ruptures on antithetic structures.

Morphologic Variation in Fault Scarp Profiles From the Stillwater Seismic Gap Associated With Hydrothermal Alteration

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Fault scarp morphology can yield paleoseismic information relevant to the age and slip distribution of surface rupturing events. However, bedrock characteristics and geomorphic modification also contribute to scarp form. Additional complications arise in fault zones in geothermal fields, where hydrothermal alteration and mineral precipitation modify the properties of the fault scarp materials. We present a case study from Dixie Valley, Nevada, where three adjacent units (lacustrine gravels, quartz-rich sinter and silicified gravels and clay-rich, acid sulfate alteration in a zone of ongoing fumarole activity) are offset by a single Holocene fault rupture in the Stillwater Seismic Gap segment of the Dixie Valley fault.

We examined the characteristics of scarp-normal topographic profiles in each unit. In the lacustrine deposits, scarp profiles have a mean height of 6.2 (±0.9) m and exhibit low along-strike morphologic variability, with typical forms displaying rounded convex-upward crests and concave toes, with linear mid-slopes. The sinter-rich section of the scarp, with a mean height of 5.8 (±0.8) m, exhibits a high degree of along-strike variability, ranging from broad concave-upward slopes to multi-tiered free faces and convex notches. A competent, silica-rich layer forms a small (~0.5 m) free face in the upper portion of many profiles. In the fumarole-altered materials, the individual Holocene rupture is difficult to discern, likely due to modification by active fumaroles, but a larger composite scarp is apparent, with concave-upward slopes, punctuated by convex irregularities associated with fumarole vents and Holocene sinter. Our case study emphasizes the need to consider composition during paleoseismic interpretation of fault scarps, particularly in hydrothermally active areas and illustrates the utility of along-strike morphologic variability in determining lithologic boundaries.

Rates and Kinematics of Active Faulting on the Western North Olympic Fault Zone

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In the Cascadia subduction zone of Washington state, upper plate contraction manifests as conjugate strike-slip faults flanking the northern and southern margins of the Olympic Mountains. The northern bounding fault, the North Olympic Fault Zone (NOFZ), strikes roughly west-northwest, parallel to the Strait of Juan de Fuca, and exhibits a post-glacial dextral slip rate of 2 mm/yr. Surficial geological mapping based on new airborne lidar data demonstrates that the fault zone extends an additional 30 km along strike to the west, indicating potential earthquake rupture lengths up to ~90 km. Here, we use field and lidar data to map and describe fault scarps along the western NOFZ to evaluate structural and earthquake connectivity with the eastern NOFZ. Scarps in the study area displace Quaternary glacial and post-glacial fluvial deposits although much of the fault trace is buried by surficial deposits or expressed solely in bedrock. Preliminary field and lidar analyses reveal that dextral geomorphic offsets of post-glacial incised channels range up to ~30 m with most values between 10-15 m. Initial analysis of vertical separation data reveal an average ~8 m with most values between 1-5 m. These analyses suggest that the post-glacial faulting is predominately dextral, similar to kinematics observed further east on the NOFZ. While we find that the strike and general kinematics of the western scarps are consistent with the eastern NOFZ scarps, the western scarps described here are significantly more segmented and discontinuous. Extending the NOFZ rupture length has the potential to increase theoretical moment magnitudes from a full-fault rupture from Mw 7.1-7.3 to Mw 7.5. New luminescence ages from samples of glacial and post-glacial surfaces cut by the fault will constrain slip rates and help us further relate the western scarps to the eastern NOFZ.

Stochastic Analysis of Hydraulic Fracturing-induced Seismicity and Seismogenic Potential Distribution in NEBC and Alberta, Canada

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Induced seismicity associated with unconventional reservoir development exhibits a high degree of spatial concentration. Induced earthquakes occur by reactivation of pre-existing crustal faults, but our knowledge of the location and geometry of faults in the subsurface is typically limited. Fault systems therefore are a key element of seismic risk hazard assessment and development of mitigation strategies. In this study, we use a stochastic approach to investigate the influence of complex fault structures on the distribution of induced seismicity and seismogenic potential of hydraulic fracturing (HF) operations in the Montney Formation, western Canada. Using synthetic induced seismicity catalogs linked to drilling locations, we have tested the influence of recently compiled large-scale structural corridors within the Montney play, including areas where seismic risk mitigation regulatory measures have been implemented: 1) North Peace Ground Motion Monitoring Area (NPGMMA); 2) Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA). Seismogenic activation potential of unconventional wells, previously determined independently using a machine learning approach, is also considered. Our statistical analysis shows that seismicity trends are best explained by a model that incorporates both structural corridors and seismogenic activation potential.

Updated Estimates of Vertical Deformation Across the Indio Hills, Southern San Andreas Fault, California

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Left-stepping strands of the southern San Andreas Fault at Indio Hills and adjacent Edom Hill cause exhumation and erosion of Pliocene and Pleistocene sedimentary rocks and provide a setting to test kinematic models of strain transfer on a complex fault system. The geomorphology of the 22-km-long range of hills varies along its length: the northwest end is mantled in eolian sand, whereas the southeastern half of the hills are capped by a late Quaternary pediment. We expand a previously reported dataset (Scharer et al., 2015 AGU) and consider 10Be abundances from 11 detrital samples (for catchment-averaged erosion rates) in relation to one eolian sample, a Pleistocene bedrock sample, and published rates from a Holocene alluvial terrace. Notably, the 10Be concentration of the eolian sand overlaps with the detrital concentration from four smaller catchments in the northwest half of the hills; a fifth, much larger catchment there has lower 10Be values. The pattern suggests eolian input may have contaminated the detrital samples and calculated erosion rates would be minimums. Toward the southeast end of the hills, detrital 10Be values are higher than the eolian and bedrock samples, and equal or higher than the terrace sample, suggesting reduced influence of the windblown sand and perhaps increased contribution from the slowly eroding pediment. Overall, the 10Be data, supported by geomorphic characteristics along the hills, show a minimum of a four-fold increase in erosion rates from 0.05 in the southeast to >0.2 mm/yr in the northwest. Although the eolian input obscures spatial details of strain transfer amongst the fault strands, the increase in the erosion rates suggests strain transfer is highest at the northwest end of the hills. This pattern is consistent with recent geophysical data and mechanical models that show a moderate northeast dip to the San Andreas Fault in the northern Coachella Valley produces a northwest-increasing gradient in uplift along the hills.

Advances in Geophysical Sensing

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: William S. D. Wilcock, University of Washington (wilcock@uw.edu); Paul Bodin, University of Washington (bodin@uw.edu); Spahr C. Webb, Columbia University (scw@ldeo.columbia.edu); Erik K. Fredrickson, University of Washington (erikfred@uw.edu); Dana A. Manalang, University of Washington (manalang@uw.edu)

Multiplexing Optical Sensors for Expanded Geodetic and Seismic Coverage of the Seafloor

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Sensors based on optical measurement of displacement have been demonstrated to have the sensitivity and dynamic range to cover a number of geodetic and seismic problems. In particular, a three component seismometer based on optical interferometric tracking of the displacement of free pendulums serves as both a broadband seismometer as well as a tiltmeter and a gravity meter. Similarly, an optical fiber strainmeter aimed at detecting crustal deformations at periods appropriate for slow slip phenomena also works well at traditional seismic periods.

Optical fibers are very efficient at transmitting optical signals, losing only about 0.2 dB per km. Modern diode lasers are extremely efficient and reliable, and optical fiber components that include wavelength dependent splitters and polarization independent reflectors are readily available and inexpensive. These factors can be combined to create an array of seismic/geodetic sensors multiplexed to span a large distance (of order 100 km) that can be interrogated by a single, low power (less than 5 watts) electro-optic system. Such a system, that is entirely passive except for the low-power interrogator at one end of a plate-scale-length optical fiber cable, enables broad coverage of the seafloor without the expense of a cable crossing the coastal boundary. Such a configuration could be made useful both for basic science studies and practical applications like earthquake early warning.

Understanding and Exploiting Ocean Wave Signals in DAS Data

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Ocean-bottom distributed acoustic sensing (DAS) records in shallow water are dominated by ocean surface gravity wave (OSGW) signals. However, the relationship between axial strain in a buried optical fiber and conventional oceanographic quantities is not immediately clear. In this presentation, we examine ocean waves recorded on a buried power cable in the Strait of Gibraltar. First, we offer a qualitative interpretation of these signals, which include wind waves and swell along with evidence of wave-current interaction. Then, we demonstrate that the scaling of OSGW amplitude and bandwidth with water depth are both consistent with seafloor compliance theory, establishing a framework for quantitative interpretation. Finally, we offer several examples of potential applications, including depth profiling along the cable, spatio-temporal monitoring of ocean currents and measuring the OSGW directional spectrum. We conclude that ocean-bottom DAS has broad potential to study ocean-solid earth interaction and complement existing oceanographic instrumentation.

Digital Quartz Crystal Seismic and Oceanic Sensors

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New seismic and oceanic sensors based on resonant quartz crystal technology have been developed for disaster warning, geodesy, climate change and other high-precision geophysical measurements. These inherently digital sensors operate in the time domain with orders of magnitude improved performance compared to traditional analog transducers. Quartz crystal absolute pressure gauges, triaxial accelerometers and rotation sensors measure short-term events like tsunamis and earthquakes with a low noise floor over an extended frequency spectrum. The pressure sensors cover the ranges from the continental shelf to the deepest ocean deployments with parts-per-billion sensitivity. New seismic sensors include omni-directional triaxial accelerometers with

+/-15 m/s^2 range and resolution better than one part per billion, tiltmeters with a +/- 1 m/s^2 range and a noise floor of ~1.5e^{-10} radian/root(Hz) at 1 Hz and broadband rotation sensors that separate linear accelerations and tilts from rotational inputs with a noise floor of ~45 pico-radian/root(Hz) near 1 Hz. In-situ calibration methods have been developed that eliminate pressure sensor and accelerometer drift to allow long-term measurements of geodesy and sea level changes. Seismic + Oceanic Sensors (SOS) modules have been developed for use on cabled systems, remote ocean bottom recorders and in underwater vehicles. These complete geophysical measurement systems will meet the vital measurement needs of seismologists and oceanographers in the coming decades.

Demonstrating a Kalman Filter Fusion of Acceleration, GNSS and Rotational Sensors Using a Flexible Foot Bridge

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The next generation of high-quality monitoring stations for strong ground motions may extend beyond an accelerometer to also include a GNSS station and a rotational sensor. Co-location of these additional sensors enables not only a broadening of the frequency range with GNSS displacements, where lower frequencies are better captured, but also the correction for rotations that corrupt inertial accelerometers during strong shaking. The development of such a monitoring station needs testing across a wide variety of motions, including, but not limited to, impulse, long period motion, tilt, torsion, small and large amplitudes. We setup our collocated accelerometer, high-rate GNSS antenna/receiver and rotational sensor in the middle of a flexible 100 m long foot bridge in Switzerland. We first characterized the dynamic response of the bridge by exciting the various modes by hammering, jumping on and then twisting the bridge at different locations along its length. We then simulated significant earthquake-like motions by jumps that excited high-frequency modes followed by twisting to excite lower frequency modes, roughly corresponding to body- and surface-wave arrivals. The high amplitude excitation of a large range of frequencies in translation as well as rotation allows us to demonstrate the benefits and more importantly the indispensability of using all three instruments.

Displacements in the cm-range and rotations of up to 0.15 rad/s were recorded. Such large rotations highly influence the accelerometer and GNSS measurements, making it necessary to correct for the gravitational leakage into the horizontal acceleration components and the tilting of the GNSS antenna pole. We show how such a correction can be applied with a Kalman filter that allows the recovery of tilt- and torsion-free translation recordings with a broad frequency band. Such a monitoring system can be used to monitor earthquake strong motion with unprecedented fidelity and also to characterize structural response with a single station.

Observations of Natural and Induced Seismic Events Using Slim Borehole Adapted SiA Sensors

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Over the past 4 years we have adapted Silicon Audio interferometer-based sensors for making seismic observations in ~100 to 1000 m deep slim-boreholes. SiA sensors use a modern, miniature electronics equivalent to a classical optical interferometer, sensing fringe position shifts resulting from the coil movement of a standard spring seismometer. The shifts are used to rapidly and accurately control a force-feedback circuit that opposes the fringe shift/coil movement. The current ~60 mm outer diameter triaxial SiA sonde has been installed in drillhole with inner diameters as small as 76 mm and tilts as large as 15°. These sensors have a 3 dB frequency-response bandwidth of 120 s to 1300 Hz, a clip level of +0.5 g and a dynamic range of 172 dB over a 1 Hz band centered at 1 Hz. This range requires data logging with a resolution of greater than 28 bits. During a rapid, less than 1 sec long tilt event, they settle with a 60 s long exponential decay.

Deployed in various settings—ranging from a plate boundary to a laboratory mine and a subsidence site—these sensors have returned complete seismograms for nearby events ranging in size from M < -1.5 to M> 4.5. In side-by-side comparisons to standard high-gain 4.5 Hz coil-spring seismometers, the SiA sonde's ~1-10 s seismic event spectrum is marketed well above background noise. At the plate boundary, the borehole SiA improved event detection over the local surface net by as much as 1 unit in magnitude. During a small-scale hydraulic stimulation experiment, a borehole SiA sonde a few tens of meters away from an injection point recorded numerous many second long events, possibly representing tilt events during hydraulic stimulation.

Advances in Geophysical Sensing

Poster Session · Wednesday 20 April · Conveners: William S. D. Wilcock, University of Washington (wilcock@uw.edu); Paul Bodin, University of Washington (bodin@uw.edu); Spahr C. Webb, Columbia University (scw@ldeo.columbia.edu); Erik K. Fredrickson, University of Washington (erikfred@uw.edu); Dana A. Manalang, University of Washington (manalang@uw.edu)

Digital Low-noise Optical Seismic Sensor

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To capture the full performance of the Silicon Audio optical interferometer-based seismometer we developed a complete digital sensor system. High levels of integration allow for compact, low mass and high-performance sensor installations.

The sensor system includes double digitizers to cover 183 dB of dynamic range and a unique in-situ laser-based sensor calibration. The high dynamic range makes the system suitable for aftershock studies with clip level up to +/-2g. Rapid deployment and remote locations would benefit from the rugged packaging and low size, weight and power.

Integrated solar charge controllers simplify installation and battery life management. The embedded Linux system allows for flexibility in system integration using standard communication protocols and an expandable architecture.

Evaluating the A-0-A Method for In-situ Calibration of Seafloor Pressure Gauges at Axial Seamount

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Measurements of seafloor pressure are an important tool for marine geodesy in settings including subduction zones and submarine volcanoes. The most sensitive and widely used pressure gauges manufactured by Paroscientific drift at ~1 part in 10^4 per year at rates that cannot be determined based on pre- or post-deployment calibrations. This requires that the gauges be calibrated in situ if the observations are to be used for measuring secular tectonic strain or slow rates of volcano inflation. The A-0-A calibration method uses a valve to temporarily switch the measured pressure from ambient to atmospheric pressure inside the instrument housing where reading is compared with an accurate barometer to measure gauge drift. A 30-month test of this method at 900 m depth on the MARS cabled observatory showed that the calibrated pressures for two redundant pressure gauges within one instrument were consistent to 1 part in 10^6 per year and matched trends in seafloor pressure inferred from combining altimetry and hydrographic data. Since July 2019, we have been conducting a second test at 1500 m depth on the Ocean Observatories Initiative Regional Cabled Array at Axial Seamount using an instrument design that incorporates a compact valve and low power electronics suitable for long term autonomous deployments. Early in the test there were several anomalous calibrations that may be related to a temporary blockage of the valve and the calibrated measurements were inconsistent between two pressure gauges. However, for the past 18 months the calibrated pressures have been consistent to 1 part in 10^6 per year after discarding 2 more anomalous calibrations. We will present up-to-date results from this test and a comparison with two other means of in situ calibration being implemented at Axial Seamount, one using repeat surveys with a mobile pressure recorder and the other calibrations with a piston gauge.

Improved Resolution Across the Global Seismographic Network: A New Era in Low-frequency Seismology

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The Global Seismographic Network (GSN) is a global network of ~150 very broadband stations and is used by researchers to study the free oscillations of the Earth (~0.3 to 3 mHz) following large earthquakes. Normal mode observations provide information regarding the radial density and anisotropic velocity structure of the Earth (including near the core-mantle boundary) but are infrequently made due to the poor signal-to-noise ratio at very low-frequencies. Most normal mode observations for the past three decades have been made on Streckeisen STS-1 vault seismometers. The Streckeisen STS-6 and the Nanometrics T-360GSN have recently been installed in boreholes, postholes, and vaults at several GSN stations and GSN testbeds. In this study, we examine normal mode spectra following three M_W 8 earthquakes in 2021 and from one M_W 8.2 earthquake in 2014 to evaluate the change in GSN low-frequency performance on the vertical components. From this analysis, we conclude that the number of GSN stations resolving normal modes following M_W 8 earthquakes has increased by a factor of ~3 since 2014. These improvements will help to better understand the radial velocity and density structure of the Earth.

In-situ Measurement of Modal Rotations at a Freestanding Rock Tower

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Modal analysis of freestanding rock formations is crucial for evaluating the vibrational response to external stimuli. While conventional seismometers can be used to measure the translational components of modal deformation, recent advances in rotational seismometer technology now allow direct measurement of the rotational components of the eigenmodes. We deployed a portable, 3-component rotational seismometer for a short-duration experiment on a 36-meter-tall natural rock tower located near Moab, UT, a site where we had previously conducted modal analysis using conventional broadband seismic data and numerical modeling. Spectral analysis of rotation data was able to resolve the first three natural frequencies of the tower (2.1 Hz, 3.1 Hz, 5.9 Hz), while polarization analysis revealed the orientation of the rotation axis for each mode. Modal rotations were strongest for the first two modes, which numerical analysis predicts are full-height bending modes akin to a cantilever with horizontal axes of rotation. The third mode is a torsional mode with tower rotation about a vertical axis. Both the natural frequencies as well as the displacement and rotation axis orientations match our numerical models closely for these first three eigenmodes. Direct in-situ measurements of modal rotations are especially valuable at remote field sites with limited access and contribute to an improved understanding of modal deformation, material properties and landform response to vibration stimuli.

Inference of the Relative Strain Energy Density of Compressional and Shear Waves Using Seismic Gradiometer

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Many source discrimination algorithms that rely on the P-to-S amplitude ratio amplitudes rest on a fundamental assumption about wave polarity: e.g., P-waves are best observed on vertical component seismograms whereas S-waves are best observed on horizontal-component seismograms. However, it's well known that P and S waves can be expressed on any component, undermining the usefulness of the resulting "P-to-S" amplitude ratio. To mitigate this problem, we separate the relative contributions of the P and S portions of the seismic wavefield by estimating the strain energy density of the observed data. We derive a set of equations that decompose strain energy density of the wavefield into two terms: one that quantifies the strain energy of compressional waves and another that quantifies the strain energy of shear waves. Our method is based on the divergence and curl of the displacement wavefield. The advantage of our approach is that there is no assumption of wave polarity. Thus, our method of separating compressional and shear waves is potentially more representative of true P-to-S ratios than prior attempts based on dodgy assumptions of wave polarization. We perform a series of tests on simulated data to estimate the strain energy density of various seismic body-wave phases for two source types: a buried explosion and an earthquake. Using a simulated gradiometer to compute the required spatial derivatives of the displacement wavefield, we estimate the strain energy of the compressional and shear portions of the wavefield and demonstrate the validity of our method to identify these two wave types. Finally, we show that the ratio of compressional-to-shear strain energy may be a complementary and useful tool to minimize uncertainty in the discrimination between earthquakes and explosions. Sandia National Laboratories is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Infrasound Direction-of-arrival Determination Using a Balloon-borne Aeroseismometer

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Geophysical phenomena in planetary atmospheres can create low-frequency acoustic waves that travel across regional to global scales. These "infrasound" waves are usually detected using arrays of microbarometers on the ground. Recent experiments have shown that microbarometers on free-flying balloons can cross regions inaccessible to surface sensors (e.g. the open ocean), often experience lower background noise and may capture directional signals that would be missed otherwise. Airborne infrasound sensors have been proposed as a means to monitor seismic and volcanic activity on the planet Venus as well. Since pressure is a scalar measurement, a single balloon-borne pressure sensor cannot determine the arrival azimuth of an incoming signal. The response of the flight system to the impact of an acoustic wave, however, does encode directionality. We show that inertial measurement systems on balloons permit the direction of arrival of incident acoustic waves to be determined and that multiple floating stations (or repeating events) allow the origin of the signal to be resolved. This technique, which we call *aeroseismometry*, is a promising solution to the dilemma of signal arrival azimuth determination on balloons: the required horizontal aperture of a traditional array cannot be supported on a single flight system and multiple independently flying sensors usually cannot be kept close enough together. We describe results from field campaigns as well as present progress on acoustic impulse response modeling and geolocation algorithms. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Next Generation Regional Arrays for Strong and Weak Motion Using Cascadia 120 Slim Posthole

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Existing regional and EEW networks can be improved in data quality, providing more stations with unclipped continuous waveform observations and a uniform magnitude of completeness (Mc). This is possible using upgraded deeper sensor emplacements and new instrumentation, based on a current understanding of system noise and updated equipment available today. Station density is increasing with the US EEW buildout, with a focus on mini-

mizing latency, which also presents an opportunity to improve data quality for weak motion. Mc and signal-to-noise ratio across the seismic and geodetic spectrum will be important for future OEF challenges and for hazard and science efforts such as 4D studies and the proposed new plate boundary type observatories, SZ4D and RuFZO. Recent development of network Mc simulation code by the USGS (Wilson et al., 2021) can be used to plan new networks, or infill stations to economically upgrade existing networks to these new best practices.

An instrument system that provides high-gain weak motion data in precise alignment with strong motion data allows combined processing to create a seamless data set with maximum dynamic range. The Nanometrics Cascadia 120 Slim Posthole has been designed to meet these requirements. Both weak and strong motion sensors are integrated in a single case which enables lowest system noise, unclipped observations and precise coherence of signals between the weak and strong motion channels. Cascadia 120 Slim and Cascadia Compact are deployed in networks now and we will present data showing the noise floor for weak motion, a seamless transition to strong motion and high coherence between the two sensors for mid-sized events.

Recent Improvements in Very Broadband Seismometer Self-noise Performance Embodied in the New Trillium 360 GSN Instruments

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Nanometrics new Trillium 360 GSN seismometer embodies the culmination of many years of research and technology innovation as well as extensive collaboration with and input from the scientific community interested in very broadband seismometry. Several generations of seismometers with 240 or 360 second corner frequency have demonstrated successive improvements in self-noise at both very low and high frequencies. The most recent development has produced the lowest self-noise of any vault seismometer and is the only seismometer currently being manufactured that meets the performance requirements of a primary seismometer for the Global Seismographic Network.

Posthole, Borehole and Vault form factors are available and being manufactured and delivered to the GSN. Performance testing of several units of each model type has been carried out at the facilities of GSN participating member institutions. The results of the performance testing are reviewed and interpreted and compared with other co-located instrument types including the venerable STS-1.

Field deployment is now proceeding, to upgrade the GSN network with the Trillium 360 GSN seismometer. We will show results from new deployments as available at the time of the 2022 SSA conference. We will also present the Trillium 360 roadmap, with a smaller low-power version for ocean bottom and portable land deployments in development for 2022 and early test results as available.

Results From a Novel Self-calibrating Tiltmeter at Axial Seamount

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Measurements of tilt are often used to characterize volcanic deformation and aid in the interpretation of complex signals from other sensors. However, short baseline tiltmeters are subject to significant instrumental drift, on the order of 10-100 mrad/yr, that is unique to each instrument and can vary over the deployment interval. As a result, though tiltmeters are capable of several nrad resolution (elevation change of several mm over 1 km horizontal), their measurements are in practice only considered reliable for short-period or large-amplitude signals. We present results from a novel tiltmeter, the Self-Calibrating Tilt Accelerometer (SCTA), capable of measuring its own drift. The SCTA comprises a tri-axial quartz crystal accelerometer developed by Quartz Seismic Sensors Inc and calibrations are performed by periodically rotating the horizontal channels into the vertical where the acceleration of gravity is used as a reference acceleration. Using data from a ~15 month onshore deployment in a vault at Piñon Flat Observatory and from a ~38 week deployment offshore at Axial Seamount's, we show that tilt measurements from the SCTA can be drift-corrected to the order of 1 mrad/yr. In the vault, where temperature fluctuates seasonally by a few centigrade, we show that tilt measured by the SCTA is sensitive to these fluctuations, but the effect can be corrected using the instrument's internal temperature sensor. At Axial Seamount, the temperature fluctuations are over an order of magnitude smaller, are dominated by frequencies well below seasonal and do not significantly impact the tilt. Additionally at Axial, data from the SCTA agree with those from a collocated LILY tiltmeter, both capturing the relatively large signal of the seamount's ongoing inflation. However, notably lower noise levels on the SCTA provide more sensitive observations of the time-variant inflation behavior and other phenomena such as the tidal deformation of the seafloor.

Seismic Data Acquisition for Portable Deployments—A New and Transformative Approach

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The focus on undertaking portable seismic campaigns has traditionally been on optimizing the costs associated with the physical attributes of the instrumentation being used—namely Size, Weight, and Power (SWaP). However, looking instead from the perspective of the overall campaign lifecycle, there are several overlooked phases that have a large impact on the success of campaigns. Decisions made during the deployment planning phase of the lifecycle regarding network size, station geolocation, instrumentation and sensor choices are fundamental. The data management problem associated with ensuring that the most up-to-date information associated with the plan is very important. Often overlooked is the importance of accurately tracking what actually was deployed in the field relative to the plan since adjustments to the plan often occur despite best intentions earlier on in the campaign lifecycle.

The Pegasus Portable Digital Recorder is part of an ecosystem of hardware and software components for portable seismic monitoring that fundamentally transforms how seismic campaigns are conducted. This integrated ecosystem-based approach to seismic data acquisition ensures that campaigns are easy to plan and execute and achieve superb outcome certainty and cost efficiency. A range of Pegasus models have been designed specifically to support Portable, Polar and OBS campaigns. Seamlessly integrated workflows address all aspects of the campaign lifecycle from pre-planning to pre-configured deployments, harvesting ready-to-use complete data sets, configuration distribution to field technicians and automatically generated metadata.

The Next Generation Compact Broadband Seismometer: Güralp Certis

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Seismic monitoring systems are continuously reducing in size and power consumption to facilitate larger scale and more remote experiments.

Güralp have been leading the way to develop a portable, user-friendly broadband seismometer that is robust, omnidirectional in its operation and maintains excellent low-noise performance. The Certimus, released in 2020, incorporates this omnidirectional sensor technology with the Minimus digitizer in a single package to provide a proven broadband station. Now, the analogue sensor component has been packaged into a robust and compact stainless-steel housing that is suitable for post-hole and surface deployments, known as the Certis.

Certis enables users to deploy in dynamic environments, without the need for cement bases or precise levelling, as the sensor will automatically adjust to tilt using internal electronics. Due to its small size, low weight and low power consumption, Certis significantly reduces the logistical requirements for broadband posthole deployments. In addition, the lack of levelling required allows for Certis to be easily deployed down hole without the need to manually adjust the sensor's orientation.

Certis has a wide frequency range of 120s to 100Hz with a remote, user-selectable long period corner. The Certis design is compatible with any commercially available broadband digitizer, however increased functionality is available with the Minimus digitizer, including access to advanced SOH parameters.

Güralp has developed a range of accompanying accessories that expand on the functionality of Certis and Certimus. The Portable Power Module offers a compact power solution that can power offline stations for up to 6 weeks.

Due to portability of both Certis and Certimus, custom-designed backpacks and smart cases allow for users to easily transport multiple systems into the field. After installation of a buried Certimus, users can easily access data from the microSD card without disturbing the sensor using a Surface Storage Module in line with the GNSS receiver.

Towards Installing a Very Broadband Seismometer 2.4 Km Below the Surface at South Pole, Antarctica

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The U.S. government has operated a seismometer at South Pole, Antarctica since the construction of Amundsen-Scott station in 1957. Although the station is highly utilized for both the detection and location of global earthquakes as well as cryoseismology, long-period (> 40 s) noise levels compromise ambient ground motion observations on all three of the station's borehole broadband seismometers. These high noise levels arise from both instrument self-noise and susceptibility to magnetic field variations, and ultimately compromise the ability to make unique normal mode and tidal loading observations at the rotation axis of Earth. To improve long-period seismic observations at the South Pole, the U.S. Geological Survey is working with the IceCube Neutrino Observatory to install a modern, very broadband seismometer at 2.4 km depth within the Antarctic icecap. There are many challenges with the deployment, including: 1) the development of a cold-rated, magnetically shielded very broadband seismometer and digitizer package; 2) mounting this package within a pressure vessel; 3) attaining accurate timing downhole; and 4) communicating with the sensor package using IceCube electronics. We will discuss progress on overcoming these challenges, many of which will likely be common to the design of quasi-permanent, ocean-bottom seismometer packages.

Advances in Geospatial Modeling of Seismic Hazards

Oral Session · Wednesday 20 April · 2:00 PM Pacific

Conveners: Weiwei Zhan, Tufts University (weiwei.zhan@tufts.edu); Xuanmei Fan, Chengdu University of Technology (fanxuanmei@gmail.com); Laurie G. Baise, Tufts University (laurie.baise@tufts.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin.zhu@gfz-potsdam.de)

Nowcasting Earthquakes with Machine Learning: The Role of Strain Hardening in the Earthquake Cycle with Implications for Slow and Silent Slip Events and Current Earthquake Hazard

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Nowcasting allows an estimation of the current state of the earthquake cycle using proxy state variables. In previous work, we used small earthquakes to construct state variable timeseries to estimate the current state of hazard for large damaging earthquakes. Here we discuss a method based on the inter-event times of small earthquakes in the active region of interest. The general form of these timeseries is reminiscent of laboratory experiments on rock failure that show the process of strain hardening leading up to failure. We use the assumption that the crustal rocks in a large region within 5º latitude and longitude around Los Angeles progressively undergo a strain hardening transition as part of the preparatory process before large M>7 earthquakes. This assumption implies a transition from "seismic" small earthquake activity to "silent" earthquake activity. The latter can only be seen with geodetic observations such as InSAR and GNSS data. Using machine learning methods, including random forest and LSTM-RNN, we find that we cannot predict the large events using a one-step walk-forward approach with our state variable timeseries. However, we show that "earthquake alerts" in the large area can be defined with clear and easily quantifiable probabilities. These alerts can then be classified using machine learning methods for true positives, false positives, true negatives, and false negatives. We further show that our assumption of strain hardening is supported by both InSAR and seismic data. These results suggest that the use of geodetic data, combined with seismic observations, might be used to locate the potential sites of significant earthquakes, as the transition from "seismic" small earthquakes to "silent" small earthquakes progresses. Further work will entail applying deep learning methods to extract further information from the state variable timeseries.

Development of Geospatial Liquefaction Probability Models for M5.4 Pohang Earthquake, South Korea

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Pohang earthquake with a moment magnitude (M) of 5.4 caused approximately 600 sand boils and ground disturbances (e.g., settlements, cracks and lateral spreadings), which are the results of liquefaction, on the Quaternary sediments in Pohang, South Korea (Ghim et al. 2018). This was recorded as the first case of liquefaction in South Korea and drew special attention because the liquefaction-induced sand boils were triggered by an earthquake with a relatively small magnitude, unlike others that were generally triggered by earthquakes with M greater than 6.0. There are several attempts to develop geospatial liquefaction probability models for assessing liquefaction hazards based on geospatial information and logistic regression (e.g., Bozzoni et al. 2021; Rashidian and Baise 2020; Zhu et al. 2015; Zhu et al. 2017). In this study, we develop five geospatial liquefaction probability models (i.e., four logistic regression-based models and one random forest (RF)-based model) using 598 sand boils that occurred in Pohang and seven explanatory variables (i.e., peak ground acceleration (PGA), slope-derived average shear wave velocity of the upper 30 meters (VS30), standard penetration test (SPT) N value, depth to rock (Drock), compound topographic index (CTI), distance to a river (dr) and roughness). To evaluate model performances for six models (i.e., the five models and one global model (Zhu et al. 2015)), we calculate six indicators (i.e., accuracy, sensitivity, precision, specificity, balanced accuracy and F1 score), and the RF-based model shows the best performance. In addition, we evaluate influence of the variables used in the RF-based model. We confirm that the predicted liquefaction probabilities are consistent with the distributions of sand boils, as well as ground and building settlements.

Determination of Coseismic Landslide Hazard Using Physics-based Ground-motion Simulation: Application for the 2021 Haiti Earthquake

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Understanding the influence of seismic ground motion on landslide hazards is vital to assess associated risks to settlements and infrastructure, especially to mountainous communities. However, due to several thousands of landslides during and shortly after an earthquake and the large area they occupy, a statistical analysis must be performed to quantify the spatially distributed hazard and risk.

Using the landslide inventory from the 2010 and 2021 Haiti earthquakes, we statistically analyze the main factors contributing to the coseismic landslides occurrence. We determine ground motion intensity measures using physics-based shaking simulations with kinematic ruptures embedded in a 3D Earth model, which we calibrate using empirical ground motion models (GMM). The physics-based shaking simulations allow us to study how the source event and the site effects, especially topographic effects, influence coseismic landslide occurrence. Ground-motion simulations generate time series for each point of the model domain, allowing for a more comprehensive analysis of shaking intensity than standard methods like empirical GMM. For example, the simulations provide specific intensity measures of shaking (IM's), like Arias intensity (Ia), cumulative absolute velocity (CAV), peak-ground motion (PGV, PGA) and spectral acceleration (SA_T), as well as the ground-motion frequency content.

We test the added value of the ground-motion simulations in explaining the coseismic landslide distribution. Specifically, we build a statistical model calibrated on the 2010 earthquake, from which we predict the landslides associated with the 2021 earthquake. We also do the opposite procedure by testing a calibrated model over the 2021 case while estimating landslide occurrences related to the 2010 event. The results are promising as both models suitably predict the coseismic failures. As a result, we assume they can be further explored to build future earthquake scenarios and associated coseismic landslides in Haiti.

A Geospatial Model for Site Response Complexity

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One-dimensional (1D) site response models assume vertically incident SH waves propagating through laterally constant soil layers. These assumptions, collectively referred to as the SH1D model, are widely used in site-specific ground motion predictions, although many studies have demonstrated their limitations. The term “site response complexity” (SRC) refers to the degree of discrepancy between the observed empirical transfer function (ETF) and the theoretical transfer function (TTF) computed with SH1D modeling. We present a geospatial approach to estimate site response complexity using statistical and machine learning methods with globally or regionally available geospatial proxies. Our site response data are from 114 vertical seismometer arrays in Japan’s Kiban-Kyoshin network (KiK-net) used in Kaklamanos and Bradley (2018). The SRC data are calibrated according to the Thompson et al. (2012) taxonomy that relies on two parameters, r (Pearson’s correlation coefficient between the ETF and TTF) and σ_i (inter-event variability of the ETF). We examine 18 geospatial proxies associated with site stiffness, topography, basin and saturation conditions. Using the geospatial proxies as explanatory variables, two sets of predictive models are developed: (a) linear regression models for predicting r and σi, separately; and (b) multiclass classification models for site response complexity. Our optimal SRC classification model uses the slope-based average shear wave velocity (V_{S30}), global sedimentary deposit thickness, depth to shear wave velocity of 1.5 km/s ($Z_{1.5}$) and global water table depth as explanatory variables. We generate maps across Japan for r, σ_i and SRC class, which can provide first-order approximations of site response complexity and exhibit clear patterns between SRC class and topography. LG sites are mostly located in flat sedimentary basins, LP sites are often located near mountain/basin edges, and H sites are located within mountainous areas. We conclude that a geospatial model for site response complexity is a promising first-order estimate of complexity in site response across broad regions.

A US National Vs30 Model and Map Driven by Remote Sensing and Machine Learning

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In current practice, the shear-wave velocity (V_S) time-averaged over the upper 30 m (V_{S30}) is widely used as a proxy for site effects, forms the basis of seismic site class and underpins site-amplification factors in empirical ground-motion models. Many earthquake simulations thus require V_{S30}. This presents a challenge at regional scale, however, given the infeasibility of subsurface testing over vast areas. At present, a patchwork of V_{S30} models exists in the U.S., with the USGS National “baseline” model being a regression equation based on one parameter (topographic slope). Given the growth of community datasets, satellite remote sensing and algorithmic learning, more advanced and accurate solutions are conceivable. Towards that end, this study develops a national V_{S30} model using field measurements from 7,081 sites and machine learning (ML), wherein 29 geospatial variables are used to predict subsurface conditions (i.e., V_{S30}). While these surficial predictors lack theoretical links to subsurface V_S, they correlate in complex, interconnected ways—an ideal problem for ML. The developed model shows significant improvement on unbiased test data (i.e., as compared to all existing national solutions) and is used to create a high resolution national V_{S30} map that includes coverage of Alaska, Hawaii and Puerto Rico.

Advances in Geospatial Modeling of Seismic Hazards

Poster Session · Wednesday 20 April · Conveners: Weiwei Zhan, Tufts University (weiwei.zhan@tufts.edu); Xuanmei Fan, Chengdu University of Technology (fanxuanmei@gmail.com); Laurie G. Baise, Tufts University (laurie.baise@tufts.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin.zhu@gfz-potsdam.de)

Evaluating Machine Learning Methods Applied To Physics-based Ground Motion Modeling via Proper Orthogonal Decomposition

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With the increase of machine learning (ML) applications in seismology, new research is needed to develop hybrid frameworks that combine ML with physics-based modeling. While ML methods have shown promising results for extracting information from large geophysical datasets, their black-box quality raises concerns about physical inconsistencies, especially for seismic hazard and earthquake early warning (EEW) applications. In contrast to ML, physics-based modeling is firmly rooted in first-order principles, though it generally does not incorporate real observations. Moreover, physics-based modeling is too computationally expensive for real-time predictions and may be unable to generate sufficient training data to fully train certain ML algorithms. The complementary strengths of ML and physics-based modeling motivates new research to develop hybrid models that combine the two.

In this work, we compute ground-motions (peak ground velocity and pseudo-spectral acceleration) for synthetic earthquakes with varying focal mechanisms and depths. The simulated data also include the effects of a southern California 3D velocity model (CVM-H) and corresponding topography. We decompose the data we generate using proper orthogonal decomposition to create reduced order models. In these models, we compare the interpolation accuracy of radial basis functions against machine learning algorithms (neural networks, k-nearest neighbors and decision trees) on forward models withheld from the training dataset. We find the radial basis function performs well with the limited amount of synthetic data; the machine learning algorithms approach comparable performance when provided with supplemental training data generated by the reduced order model. We envision these surrogate models will be useful in next-generation EEW algorithms that require computationally-efficient forward operators to compute real-time predictions using ground-motion observations and wave propagation physics.

Exploring the Potential for SAR Phase to Capture Soil Moisture Variability to Improve Earthquake-triggered Ground Failure

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Earthquake-triggered ground failure, including liquefaction and landsliding, is a challenging process to model and is also a hazard that contributes significantly to damage and losses. Soil moisture conditions are a primary factor that affects susceptibility to both types of ground failure, and soil saturation is required for liquefaction to occur. However, soil moisture conditions are difficult to measure, both in terms of annual averages as well as seasonal variations. Our goal is to incorporate remote sensing-derived data into a ground failure model to provide constraints on soil moisture. Here, we explore the utility of Synthetic Aperture Radar (SAR) phase data in retrieving surface and near subsurface soil moisture. While the impact of soil moisture variability on SAR data is difficult to isolate, recent studies have found that utilizing the full dimensionality of SAR data can shed new light on how soil moisture affects SAR amplitude and phase. In this study, we analyze Sentinel-1 data collected between November 2016 to March 2017 near San Jose, CA, and derive several products that exploit the full dimensionality of SAR data, including polarization, triplet phase closure, and coherence. We compare these results to ground-truth soil moisture data collected by the USGS during the same

period. In addition to soil moisture information, SAR data is used to generate maps that correlate with earthquake-induced infrastructure damage by comparing pre- and post-SAR acquisitions. Because soil moisture may also vary between SAR acquisitions, it is one of the main contributors to the uncertainty of post-seismic damage and ground failure maps. Thus, a better understanding of the effects of soil moisture on SAR data may lead to improvements in the accuracy of SAR as a tool for detecting surficial earthquake-related changes, which have been used to identify structural damage and ground failure features.

Geology and Geomorphology Based f0 Model of New England

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Earthquake site response studies are needed to estimate ground motions and quantify seismic hazard. Whereas site-specific studies analyze individual locations and compute 1D, 2D or 3D ground response at that location, regional studies integrate many pieces of information to develop a general understanding of a particular geologic unit, or an entire region composed of many geologic units. In this study, a regional f_0 model of New England is developed by integrating geologic polygons, categorical subregions, river buffers, distance to coastlines and topographically derived geomorphic parameters. New England is a glaciated terrain and site response is controlled by the sediment thickness and the high impedance contrast between sediments and hard bedrock. f_0 derived from HVSR analysis provides a useful tool for regional site response studies because it is inexpensive and easy to collect over large areas, contains both velocity and depth information, and is known to be especially effective in high impedance environments. For this study, we compile 1627 f_0 measurements and geospatial proxies (slope, CTI and others) and stitch together a surficial geology map of New England based on existing state-based maps. In addition, we identify five geologic subregions of interest: Connecticut River Valley, Boston Basin, Southern Moraine Terrain, Champlain Sea Sediments and the Maine Coast. The f_0 data and predictor variables are explored and general f_0 patterns are identified. Our first product is a geology-based f_0 map of New England. Within this map, velocity information is added by subregion allowing the computation of sediment thickness (d) and average shear-wave velocity (Vs_{avg}) in the sediments. With these three values, f_0, Vs_{avg} and d, Vs30 based site class and other earthquake engineering parameters are estimated. Our second product is a geospatial proxy based f_0 map of New England. This map is derived empirically using regression techniques and continuous and categorical geospatial and geologic site response proxies. Both maps provide information on regional trends for site response for New England.

Geospatial Mapping of Seismic Hazards: An Example of Site Amplification Mapping in the New Madrid Seismic Zone of Central United States

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Ground motion can be significantly amplified at certain frequencies by near-surface, low-velocity sediments, which is known as site amplification or site response. Site response is of great concern in the New Madrid Seismic Zone because there are many areas underlain by soft sediments overlying hard bedrock. Many different site-response proxy maps have been produced, including the NEHRP site classes (based on the time-weighted average shear-wave velocity of the top 30 m of the soil/rock column, i.e., Vs30), surface geology and topographic slope. Although the NEHRP site class and other proxy maps have been widely used in regional seismic hazard and risk assessments, we have found that these maps may not reliably predict site amplification, in large part because they may not account for resonance effects. Other maps, such as fundamental (or dynamic) site period (or frequency) and peak spectral amplification, have also been produced for the region. Thus, an evaluation of the various maps is needed to determine which is most useful for practical applications. In this study, we reviewed the basic characteristics and primary parameters for site amplification in the New Madrid Seismic Zone and then evaluated the NEHRP site class, surface geology, topographic slope and fundamental site period and amplification maps against the primary site parameters. Our results show that there is no single map that can sufficiently capture the site amplification, and that the fundamental site period and its associated amplification maps are the most appropriate for quantifying regional site amplification because they directly capture the primary parameters of site amplification. Our results also show that the sediment thickness and ratio of bedrock shear-wave velocity to sediment average shear-wave velocity are the best paired proxies for predicting regional site amplification because they have the highest correlation coefficients with the primary site parameters.

Global Geospatial Liquefaction Model Updates Using Advanced Machine Learning Algorithms

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Data-driven geospatial liquefaction models are useful tools for real-time post-event impact and regional seismic hazard assessments. Geospatial liquefaction models are based on liquefaction occurrence inventories, widely available geospatial variables and earthquake-specific parameters. We have updated our inventory with geospatial data from non-liquefaction and liquefaction occurrence locations in 51 earthquakes around the world. This geospatial data includes one categorical and 17 continuous variables representing proxies for soil saturation, soil density and earthquake loading. In our prior work, logistic regression was used to present an updated global geospatial liquefaction model (Baise et al., 2021). In this presentation, we evaluate advanced machine learning (ML) algorithms as an alternative approach. ML techniques enable to deal with imbalanced data and to find complex nonlinear patterns in the large dataset, but they can be prone to overfitting. The proposed methodology starts with an exploratory data analysis of all variables to detect outliers, run data transformations and perform a statistical comparison between the two classes. Bivariate statistical analysis is also performed to remove redundant information. The dataset is then balanced in terms of classes and events, which necessitates synthetic data generation for the earthquakes with a very low sample number. An ML-based feature selection approach is also implemented to remove the variables with low weight or harmful impact on the classification model. Finally, the ML-based binary classification model is trained with Bayesian optimization using the remained variables and samples and validated via a K-fold cross-validation approach. To check the model reliability and potential bias, the leave-one-out testing approach is used to independently test the model by removing one earthquake at a time. The results of this study are compared with the model developed using logistic regression to investigate the benefits and limitations of applying ML algorithms.

Ground-motion Modeling Using Machine Learning Techniques and Geospatial Proxies

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Ground-motion modeling plays an important role in seismic hazard assessment. Despite a tremendous increase in the number of ground-motion models, the aleatory variability of ground-motion modeling has shown little or no decrease since the 1970s. In this work, we aim to reduce the aleatory variability of ground-motion modeling by integrating nonparametric machine learning techniques and inexpensive geospatial proxies associated with earthquake path and site effects. We use a gradient boosting model (GBM), which is a decision tree ensemble method that improves the model accuracy by iteratively adding new decision trees that correct errors from prior iterations. To train and evaluate the GBM-based ground-motion models (GBM-GMMs), we select 17,082 recordings associated with 436 earthquakes from the Next Generation Attenuation Relationships for Western U.S. (NGA-West2) ground motion database. Using this dataset, we consider three primary predictor variables (moment magnitude Mw, Joyner-Boore distance Rjb, depth to top of fault rupture Ztor) and 24 candidate geospatial predictors associated with site stiffness, topography, basin and saturation conditions (such as slope-based average shear-wave velocity (VS30), global sedimentary deposit thickness, terrain roughness index, global water table depth and distance to the nearest river). We recommend the optimal ground-motion models by considering the tradeoff between model accuracy and model complexity. Uncertainty analysis is conducted to evaluate the contributions of models to reduce different types of variabilities. Our results show that the GBM-GMMs trained using geospatial proxies have equivalent or smaller regression errors than the GBM-GMMs trained using the primary predictors and conventional GMMs. The findings of this work illustrate both the potential of machine learning techniques and geospatial proxies in reducing the uncertainties of ground-motion models.

NSF SAGE-facility Begins Procurement of Rapid Response Instrumentation

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Geohazards cause billions of dollars in U.S. economic losses, loss of life, injuries and significant disruption to lives and livelihoods on an annual basis. The ability of the geoscience community to respond rapidly after a hazardous event, or at the start of precursors, allows for the collection of critical data to understand the physical processes responsible for these destructive events. The Seismological Facility for the Advancement of Geoscience (SAGE) is an NSF-funded facility operated by the Incorporated Research Institutions for Seismology (IRIS). As a part of the SAGE award, and after several years of gathering community input, IRIS is ready to begin procurement of a new suite of instrumentation specifically for rapidly responding to geohazard events. During the past year, staff at the IRIS/PASSCAL Instrument Center have conducted instrument testing and evaluation to inform the preferred mix of instrumentation for the new rapid response equipment pool—which is expected to include broadband and nodal seismometers, digitizers, and infrasound sensors. This effort has been guided by recommendations from a Rapid Response Community Whitepaper, with ongoing oversight from the PASSCAL Standing Committee. A copy of the whitepaper, as well as recordings and presentations from hosted gatherings have been posted to IRIS' Rapid Response to Geohazards webpage (www.iris.edu/rapid).

With testing and evaluation complete, IRIS is looking ahead to procuring instruments and associated equipment over the next year, followed by acceptance testing and integration at the IRIS/PASSCAL Instrument Center. Concurrently, IRIS is working with community governance to formalize new policies and procedures that will outline how this new community resource can most effectively and efficiently be used for geohazard-related observations. Beginning in 2023, PIs will be able to schedule and use this equipment from the IRIS/PASSCAL Instrument Center that is operated as part of NSF's SAGE facility.

OpenAmp: A Global Seismic Site Amplification Database

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OpenAmp is a global large-scale high-quality earthquake site amplification benchmark dataset. It contains the amplification at thousands of strong-motion stations in Europe, Japan, Taiwan and the US derived from earthquake recordings in both Fourier and response spectral domains. Previously we have developed an open-source site database (OpenSite): https://doi.org/10.1177/8755293020988028 which contain ample site metadata unparalleled by any other database. These two data sets (OpenSite and OpenAmp) could facilitate the methodological exploration of AI in multi-scale (from site-specific to regional) site amplification modeling in terms of model development and benchmarking. High-quality benchmark data set can enable the direct comparison of different AI models/algorithms such that the state-of-the-art approach can be readily identified and improved on, eventually advancing our specific research field. OpenAmp can help to unleash the full potential of AI in site amplification modelling, like ImageNet in visual recognition, and the Protein Data Bank in protein structure prediction. We adopt FAIR principles (findable, accessible, interoperable and reusable) in database development. OpenAmp is an ongoing community-driven initiative, and we welcome contributions from the community.

Updated Global Geospatial Liquefaction Model Using Logistic Regression

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In recent years, there has been extensive efforts to develop predictive ground failure models for estimating the probability of liquefaction and landslide occurrence as a result of earthquake shaking. In Zhu et al. (2017), a global geospatial liquefaction model was developed considering 27 earthquakes, mostly with extensive liquefaction occurrence. In our current work, we have expanded the dataset to include 51 earthquakes with limited, extensive or no liquefaction occurrences from around the world. Liquefaction and nonliquefaction locations are sampled and the updated dataset includes a set of 18 explanatory variables for each location which represent ground motion (e.g. PGV and PGA), soil density (e.g. soil thickness and Vs30) and soil saturation (e.g. water table depth and precipitation). The collected data are resampled to provide a balanced dataset such that each earthquake has the same impact on the final model and that the liquefaction and nonliquefaction occurrences are roughly balanced. An updated global geospatial liquefaction model was then derived using the logistic regression model. Predictive performance of each explanatory variable was studied separately and in interaction with other variables to identify the optimal candidate variables as well as to detect variables with strong or moderate collinearities. The model selection process was guided considering different performance measures including Brier Score, Akaike information criterion (AIC) and area under the ROC curve. The best-fit updated models use PGV, slope-based Vs_{30}, Topographic Roughness Index (TRI), distance to closets water body, distance to river and elevation above closest water body as explanatory variables. The updated models show improved performance compared to the GGLM17 models. Regional performance of the models was also studied. It was observed that the updated models have robust regional performance for North America, Oceania, Japan and the rest of Asia while their performance is relatively less robust for Europe and South America; considering the limited liquefaction data available for these regions.

Advances in Seismoacoustic Methods for Explosion Monitoring

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Delaine Reiter, Applied Research Associates (dreiter@ara.com); Sean Ford, Lawrence Livermore National Laboratory (ford17@llnl.gov); Keith Koper, University of Utah (koper@seis.utah.edu); Fransiska K. Dannemann Dugick, Sandia National Laboratories (fkdanne@sandia.gov); Michelle E. Scalise, Nevada National Security Site (scalisme@nv.doe.gov)

Aftershocks of the Announced Underground Nuclear Tests Conducted by the DPRK Found by Waveform Cross Correlation: From 2013 to 2022

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In this work, by aftershock, we mean activity of a tectonic nature taking place later in time and not contradicting the hypothesis of very close proximity to the epicentre of the underground explosion. The first aftershock of an underground explosion within the DPRK test site was found by the method of waveform cross correlation (WCC) on 11 September 2016, two days after the fifth test (DPRK5). Tens of aftershocks were built by IDC analysts in interactive analysis after the DPRK6. Additional DPRK6 aftershocks were found by the WCC method and many of them were later confirmed by IDC analysts. A set of robust aftershocks after the DPRK5 and DPRK6 allowed to develop, test and prototypically apply the multi-master WCC method retroactively since 2009 to IMS stations KSRS and USRK. Dozens of new aftershocks of the DPRK5 and DPRK6 were found in a comprehensive data re-processing, with the most recent events observed in October and December 2021. We have also found aftershocks of DPRK3 (12 February 2013) and DPRK4 (6 January 2016), but none for DPRK2 (25 May 2009). No natural or induced seismic events with waveforms like those observed for any of the DPRK aftershocks were found between January 2009 and February 2013. The DPRK3 and DPRK4 aftershocks were also confirmed by interactive analysis. Currently, more than 100 DPRK aftershocks are found by the WCC method, with the two-station WCC relative locations not contradicting the hypothesis of very close proximity to the DPRK tests.

ML:MC Applied to Nuclear Explosions Detonated at the Nevada Test Site

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Verification of the Comprehensive Nuclear-Test-Ban Treaty relies on the effective discrimination of earthquakes and explosions. Established discriminants often use mining blasts as analogs for nuclear explosions, given the rarity of nuclear explosion seismic data. M_L:M_C is an effective depth discriminant for events recorded at local-distances and has successfully distinguished mining explosions from tectonic earthquakes in numerous regions around the world. Here, M_L:M_C was tested on a dataset that includes historic, and now rarely occurring, nuclear explosions; as well as chemical explosions, cavity collapses and tectonic earthquakes. The dataset includes 73 nuclear explosions, a subset of the 828 the United States detonated underground at the Nevada National Security Site (formerly the Nevada Test Site). It contains one chemical explosion from the Non-Proliferation Treaty and 13 chemical explosions from mining activity in Arizona. The dataset also includes four cavity collapses: two occurred in southwestern Wyoming and two were post-nuclear test cavity collapses. Lastly, there were 61 earthquakes in this dataset distributed throughout the southwestern United States. The discriminatory performance of M_L:M_C decreases with increasing magnitude and increasing distance, which we attribute to the saturation of the M_C scale. Though there are complications with this legacy dataset, we show that M_L:M_C is effective at separating nuclear explosions and tectonic earthquakes.

Moment Tensors and Explosion Monitoring

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Moment tensors capture the point-source force couples of seismic events, including explosions. In Pasyanos and Chiang (2021), we have developed a dataset of full (six-element) moment tensor solutions for 130 nuclear and 10 chemical explosions conducted at the Nevada National Security Site (NNSS). The moment tensor database (open and available) can be used in a number of ways including in event identification and yield estimation. We test explosion event screening on the fundamental lune of the moment tensor eigensphere and find this to be a robust discriminant between explosions and earthquakes in the western United States. The seismic moment for a given explosive yield varies widely due to emplacement conditions such as the depth and the strength of materials at the point of the explosion. Moment tensors of explosions can also be contaminated by secondary source effects (e.g. spalling, tectonic release), but which can be isolated through moment tensor decomposition. Explosion source models can capture the variation in the moment-to-yield ratio due to the emplacement conditions and hence be used in the estimation of yield. We first calibrate the method with ground truth (known yield, depth and material properties) explosions at NNSS and then apply it to the six declared North Korean nuclear explosions. With the use of coda derived moments, this potentially could be used to examine low yield explosions not having full moment tensor solutions.

3D Nonlinear Modeling of Underground Nuclear Explosions and the Generation of Seismic Waves

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Understanding of the explosion source is fundamental to nuclear monitoring. In spite of decades of research on this subject, there are still many unknowns, particularly when there is strong topography, tectonic stresses or multiple simultaneous explosions. We have developed a 3D Lagrangian Finite Element Code, CRAM3D, that allows calculations of complex explosion emplacement conditions and can directly address these problems. CRAM3D has been developed over more than a decade, but the history of the code is actually much longer, as it was derived from an earlier axisymmetric code CRAM developed during the nuclear containment program. Although the structure of CRAM3D is more modern and quite different, CRAM3D includes material models from CRAM that were developed over many years based on nuclear explosion data. The output of CRAM3D interfaces with code that uses the representation theorem to propagate the near-source motion to regional and teleseismic distances.

CRAM3D uses MPI to split a calculation over multiple processors and so has the capability to address very large problems. It has been used recently to model explosions at the North Korean Test Site, where topography strongly affects seismic waves; to model 13 explosions at the Degelen Mountain test site, where topography and tectonic stresses are important; and to model explosions at the Novaya Zemlya test site, which has both strong topography and multiple simultaneous explosions.

Stochastic Methods for Full Moment Tensor Inversion and Uncertainty Quantification

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We present efficient stochastic sampling methods for full moment tensor and point force inversion and uncertainty estimation within our open-source software package MTUQ (moment tensor uncertainty quantification). Accurate determination of full moment tensor and point force parameters are required for the characterization of natural and anthropogenic seismic sources, as well as for seismic tomography and nuclear monitoring applications. Most operational codes rely on grid-search methods for exploring the solution space, which limits the range of applications they can tackle. We evaluate the use of the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) and Hamiltonian Monte Carlo (HMC) samplers to increase efficiency over conventional grid search methods. The CMA-ES is a black-box optimization method that samples the parameter space by using a multivariate Gaussian distribution whose mean, covariance matrix and step size are deterministically adjusted based on the ranked n best-fitting samples of each generation. Applied to moment tensor inversion, the CMA-ES converges quickly to a solution and samples preferentially the lower-misfit region, resulting in reduced computational cost. The HMC method is a stochastic sampler relying on the gradients of the misfit function to guide an optimal sampling. Gradients are computed at a low cost from Strain Green's Function databases generated by storing the strain wavefield in the vicinity of the source region, resulting from unit vector forces injected at target stations. These sampling methods provide a natural framework for tackling complex inversions, such as joint moment tensor and source location inversions, which are challenging for grid search methods. We implemented these novel approaches in the MTUQ package, taking advantage of C-accelerated code, compact Green's function databases and parallelization for HPC applications. It has been tested on several platforms and outperforms legacy cut-and-paste codes.

Developing a Consistent Travel-time Framework for Comparing Three-dimensional Velocity Models for Seismic Location Accuracy

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Location algorithms have historically relied on simple, one-dimensional (1D) velocity models for fast seismic event locations. 1D models are generally used as travel-time lookup tables, one for each seismic phase, with travel-times precalculated for event distance and depth. These travel-time lookup tables are extremely fast to use, and this fast computational speed makes them the preferred type of velocity model for operational needs. Higher-dimensional (i.e., three-dimensional – 3D) seismic velocity models are becoming readily available and provide more accurate event locations over 1D models. The computational requirements of these 3D models tend to make their operational use prohibitive. Additionally, comparing location accuracy for 3D seismic velocity models tends to be problematic, as each model is determined using different ray-tracing algorithms. Attempting to use a different algorithm than the one used to develop a model usually results in poor travel-time prediction. We demonstrate and test a framework to create first-P and first-S 3D travel-time correction surfaces using an open-source framework (*PCalc+GeoTess*, https://www.sandia.gov/salsa3d/software, https://www.sandia.gov/geotess) that easily stores 3D travel-time and uncertainty data. This framework produces fast travel-time and uncertainty predictions and overcomes the ray-tracing algo-

rithm hurdle because the lookup tables can be generated using the exact ray-tracing algorithm that is preferred for a model.

3D SEM Modeling of Wave Propagation at the Source Physics Experiment Phase II Site to Quantify Shear Wave Generation by Explosions at Short Distance (<3km)

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Shear wave energy has been observed for most underground explosions which are classically modeled as isotropic sources. Shear waves are likely to be produced by any deviation of the actual source from an ideal isotropic source and by wave propagation in a complex subsurface where reflections and refraction will transfer seismic energy from P to S-wave. In this study, we use 3D full waveform modeling enabled by the code SPECFEM3D (Komatitsch & Tromp, 1999) to quantify the effect of different subsurface features on P/S ratio. Our goal is to explain some of the scatter observed for P/S ratio for small events and at short event-to-station distances that challenges discrimination methods (Pyle & Walter, 2019). SPECFEM3D is based on the Spectral Element Method (SEM) which is a direct numerical method that has benefited from advances in numerical methods and (super)computers over the last two decades.

Our modeling is compared to data recorded by a dense Large-N array of a series of well-instrumented chemical explosions in the Yucca Flat basin (Nevada), Phase II of the Source Physics Experiment (SPE). The four explosions of the series were carried-out in quaternary alluvium overlying tertiary tuff and Paleozoic basement rocks. A subsurface model was built using a local geological framework model and different models of seismic velocities were tested, some coming from seismic analyses, some from tomographic studies. We further varied the velocity of each geological unit in the model using Gaussian and Von Karman distributions to account for random heterogeneities. The accuracy of our modeling is assessed with different convergence tests. We compare modeled P/S ratios and peak velocities of the transverse component to the data to constraint our modeling. We found that the contrast between the tuff and the sedimentary layer is key in matching the peak velocity of the transverse component observed in the data with synthetics.

Acoustic Arrivals From Weak Explosive Sources Recorded on Distant Airborne Platforms

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Surface, airborne and buried explosions create low-frequency acoustic waves that can travel vast distances in planetary atmospheres. The near-source amplitude of these waves depends on the size and type of the explosive charge and how it was emplaced. The atmospheric state between the event and the receiver then determines whether the signal can be detected at local to global distances. This problem has received extensive attention with respect to ground-based sensors, but the detectability of explosive phenomena from airborne platforms is less well understood. In particular, acoustic signals generated by surface or buried explosions and then transmitted along a "direct" path to a high-altitude receiver have not been examined in detail. Here we show that balloons in Earth's lower stratosphere can record direct arrivals from 40 km away, and at even greater distances depending on the wind field. These arrivals preserve near-source waveform characteristics, which are often lost at these ranges on the ground. We discuss the unique propagation patterns of ground source/airborne receiver combinations in the context of three events: the DAG-4 buried chemical explosion (a 10 ton TNT equivalent charge buried 56 m underground as part of the Source Physics Experiment), a set of small surface chemical shots (100 lb. TNT equivalent) and a set of larger surface chemical shots (1000 lb. TNT equivalent). These results have implications for capturing weak acoustic emissions for ground events of interest as well as the potential for persistent stratospheric infrasound monitoring of remote volcanoes. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Non-linear Simulation of the 2020 Beirut Explosion: Energy Coupling at Ground-air-sea Interfaces, Cratering, Hydroacoustic and Seismoacoustic Conversion and Signatures

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Predicting a propagating blast wave in urban environment is a complicated task especially when dealing with a dense and a complex urban environment such as Beirut city. Furthermore, when the shockwave is simultaneously interacting with sea water, airr and ground, then it further complicates the non-linear interaction of the shockwave with the environment and its response to the urban geometry and structures. Empirical and semi-empirical engineering tools are then limited, and it is required to use state-of-the-art hydrodynamic codes which has led us to develop a physics-based framework to seamlessly simulate the event from source, chemical explosion, to ground and sea-water impacts, to wave generation, propagation. The non-linear effects of the explosion are simulated using the hydrocode GEODYN to create the nearfield source for the shallow water wave propagation code, SWWP and the ground propagation SW4. The GEODYN-SWWP coupling is based on the structured adaptive mesh refinement infrastructure; SAMRAI developed at LLNL, while GEODYN-SW4 coupling is based on mapping the explosion source as a boundary condition to SW4. We illustrate both couplings and compare them to a direct solution where all the physics are solved fully using GEODYN. Only a fraction of the total explosion energy is converted into hydroacoustic and seismoacoustic waves that have the ability to propagate beyond the source region. The remaining energy is consumed by the "evaporation" of the water and pulverization of the surrounding ground and structures. We predicted the crater at ground zero and assessed key parameters and their uncertainty on the overall hydroacoustic and seismoacoustic responses.

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Quantifying the Impact of Simulation Frequency Fidelity on Waveform-based Bayesian Inference for Seismic Monitoring Using Bayesian Experimental Design

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The detection, location and quantification of small magnitude events at local distances is an ongoing challenge in seismic monitoring. Methods to integrate waveform data from across a network could improve the detection capabilities. Because performing inference with high-fidelity full-waveforms would require computationally expensive full-waveform simulations and specifying difficult assumptions about earth structure, simplifications are needed. Current methods use derived features from waveforms, e.g., seismic phase arrival times or low frequency waveform content (typically much less than 1Hz). However, when identifying lower signal-to noise events at local scales, utilizing additional features becomes critical. This approach requires modeling seismic waveforms for different candidate events, extracting relevant features and then using Bayesian inference to integrate modeling uncertainty, sensor noise and background. The limiting factor to this approach is the frequencies that simulations need in order derive meaningful features. High frequency simulations require both more computational time and more knowledge of earth structure. Therefore, we seek to rigorously quantify the impact of simulation fidelity on our ability to identify seismic events.

We use tools from Bayesian inference and experimental design to explore the capabilities of feature-based inference when simulation fidelity is restricted to different high-frequency cutoffs. This enables us to characterize meaningful simulation requirements. We will both discuss this computational framework and present an application where we characterize simulation requirements for calibrated conditions.

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Mine Explosion Identification Using Machine Learning Methods

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Modeling and identification of mine explosions is an important task in seismic signal processing that typically relays on pattern recognition and signal processing solutions. This work focuses on the problem of identifying mine explosions that originate from a specific mine from continuous waveforms at a single seismic station. The pattern to identify is complex, as the mine spans several kilometers and the recorded blasts may be of different type, magnitude and location. Furthermore, identification of such single blasts from ongoing recordings that contain many other types of seismic signals (like originated from earthquakes and blasts from other mines), may be a challenging task.

In this work, machine learning techniques, which faithfully model high-dimensional data into a compact, low-dimensional space, are utilized. In particular, an extension of diffusion maps is applied for creating a compact representation of the mine patterns. This representation is stable with respect to the changing time streams that hold new seismic data. Additionally, manifold based data fusion techniques are implemented for processing the 3-channal seismic recordings. The capabilities of the model are presented on several different datasets and compared with deep learning techniques. In particular, at the station EIL in Israel we identify arrivals that were caused by the blasts at the Eshidiya mine in Jordan. The results highlight the method's computational and explainable proprieties.

An Alternative Multi-processor Configuration for Network Processing at the CTBTO

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The CTBTO processing step of automatic association has undergone a major upgrade with a Bayesian method, NET-VISA, being used in parallel with the legacy Global Association (GA). GA is used in a three-stage process to produce the joint seismic, hydroacoustic and infrasound automatic bulletins SEL1, SEL2 and SEL3. NET-VISA is executed at the same time as the third stage, SEL3, on the same input data to produce an alternative to SEL3, the VSEL3, partially reviewed by analysts in complement to the SEL3 since 2018. An offline test running continuously in real time has been setup where the roles of GA and NET-VISA have been switched to assess the potential of such an operational configuration. This takes full advantage of NET-VISA's better performances in terms of missed events and completeness of the association sets of its automatic events, particularly auxiliary seismic stations, thus facilitating the work of the analysts. Results of this offline test, including an assessment by an expert analyst of the resulting reviewed bulletin, are compared to the standard Reviewed Event Bulletin. Analyst review allows an assessment of the true inconsistency (false alarm) rate of the method.

Near Field Modeling of the Large Surface Explosion Coupling Experiment (LSECE)

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The Large Surface Explosion Coupling Experiment (LSECE) was conducted at the Nevada National Security Site (NNSS) site in alluvium geology. The goal of the LSECE was to study the seismoacoustic wave generation for two consecutive surface chemical explosions of the same yield and compare their effects with fully contained chemical explosions at various depths extending to almost 400 m in a nearby test hole during the recent Dry Alluvium Geology (DAG) experiment as part of the Source Physics Experiment.

We have performed 2D and 3D numerical simulations of both experiments (LSECE and DAG) to investigate the role of various factors in seismoacoustic wave generation. The constitutive model used for alluvium describes the effects of porous compaction and tensile damage (spall). It uses correlations between the material porosity and other mechanical properties such as poroelasticity and strength observed during mechanical testing of the core samples excavated from the site at various depths. Results of the simulations can be useful for developing better analytical source models both for surface and buried explosions in alluvium geology.

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A New Approach for Simulating Sound Wave Propagation Based on Lab Experiments Using 3D-printed Models

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Understanding infrasound wave propagation is crucial for monitoring volcanic eruptions and nuclear explosions. At local scales (<15 km), infrasound propagation can be complicated by reflection and diffraction from topographic features such as mountains and valleys. Effects of such features need to be quantified to obtain accurate source parameters such as size, timing and location. However, the extent of waveform distortion and energy loss due to topography is still poorly understood, because numerical models often assume flat surfaces or simple terrains and observational data, particularly in the near field, are limited. Here, we propose a new lab-based method that can simulate the wavefields on 3D-printed models with various topographic features and provide experimental datasets.

In this project, we (1) print a physical model with topography close to a sinusoidal pattern and (2) conduct experiments on the model by generating signals with laser blasts and measuring vibrations along the surface. We use pulsed lasers as sources, analogous to volcanic or nuclear explosions. Laser doppler vibrometers, which are sensitive to the motion in the air, record sound waves with dense spatial coverage. We detect air waves traveling above the model's surface at the speed of sound. Multiple arrivals are also observed in some parts of the wavefield, likely resulting from abrupt elevation changes. Using the data obtained from a flat physical model as references, we investigate how elevation changes affect amplitudes and arrival times of sound waves recorded at different locations. We also examine differences in amplitudes depending on different sizes of explosions by adjusting the source laser power. This new application of the 3D printing technique allows us to build physical models with any desired terrain. Our experimental approach using 3D-printed models will help advance our understanding of infrasound propagation and improve our ability to monitor explosions.

Verifying the Presence of an Acoustic Duct Using Balloon-borne Infrasound

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The Sound Fixing and Ranging (SOFAR) channel in the ocean allows for sound to travel great distances, making it particularly useful for detecting underwater nuclear explosions. Suggestions that an elevated SOFAR-like channel should exist at the tropopause, the interface between the troposphere and stratosphere, date back over half a century. However, there are no publications that discuss directly observing sound within this channel. We used microbarometers on solar hot air balloons in the lower stratosphere to record infrasound signals from publicly announced orbital rocket launches. These rockets crossed through the tropopause, injecting acoustic energy into the potential atmospheric duct. Here we present the first high altitude recordings of acoustic signatures from two rocket launches: (1) the Blue Origin rocket launch out of Van Horn, TX, USA on 26 April 2021 and (2) the United Launch Alliance rocket launch out of Vandenberg Air Force Base, CA, USA on 23 September 2021. Results suggest that signals can be recorded within the acoustic duct and that the acoustic background at these altitudes is more complicated than previously thought. We detail initial results and discussion on signal detection and background characteristics.

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Advances in Seismoacoustic Methods for Explosion Monitoring

Poster Session · Friday 22 April · Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Delaine Reiter, Applied Research Associates (dreiter@ara.com); Sean Ford, Lawrence Livermore National Laboratory (ford17@llnl.gov); Keith Koper, University of Utah (koper@seis.utah.edu); Fransiska K. Dannemann Dugick, Sandia National Laboratories (fkdanne@sandia.gov); Michelle E. Scalise, Nevada National Security Site (scalisme@nv.doe.gov)

A Robust Seismic Discrimination Technique for Low Signal-to-noise Events Recorded in Regions of Interest

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Seismic monitoring needs are growing in the Middle East and South Asia, especially in regions with complex seismic propagation. The lack of in-country networks to record seismic activity in these regions inhibits our ability to develop reliable discrimination techniques. As Pakistan is a country with known nuclear weapons and also has a high rate of natural seismicity, these factors increase the need for a regionally calibrated seismic discrimination method to accurately identify any nuclear explosion test among the regional seismicity. To address this need, through funding from the Department of State, we built and validated a new screening method in Pakistan based on a previously developed ARA discrimination technique that uses m_b(P-coda) and M_sU magnitude measurements to exploit properties of earthquakes and explosions to increase discrimination capability. The m_b(P-coda) and M_sU magnitude scales minimize source, propagation and radiation pattern effects, and both magnitude values are routinely measured on regional networks below magnitude 4. This discrimination method is especially useful in regions with sparse station coverage and poor signal-to-noise ratios. By building a database of over 25,000 events ($M < 3$) recorded on both in-country and out-of-country networks, we were able to successfully develop a calibrated discrimination technique for Pakistan and the surrounding region.

Automated Seismic Array Quality Control—Testing a Jackknifing SVD Method in a Python Application

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We present preliminary findings for automated quality control analysis on a seismic array over an extended time period. Our method leverages application of singular value decomposition (SVD) to explore the system of array data in a time-varying manner, identifying problematic channels on the fly that can compromise F-K anaysis and beamforming integrity for seismic arrays. We invoke a jackknifing scheme in which the system is evaluated through repeated elimination and restoration of waveforms. The resulting normalized singular value functions are evaluated for consistency, and anomalies are isolated through application of a clustering approach.

In previous demonstrations of the method, it has successfully identified and tracked calibration pulses that occlude small earthquake signals and that negatively impact F-K results. We likewise have found the tool sensitive to intermittent natural noise. We will discuss the sensitivity of the method, thresholding issues, various possible applications and our progress towards implementing an interactive GUI to drive this Python algorithm.

Characterizing Blast Wave Behavior From Cavities Embedded in Lab-scale Polymer Cubes

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Wavefield interactions with cavities and void-filled damage zones play an important role in the near-field seismic signals generated by underground conventional and/or chemical explosions. Here, the interactions of blast waves with voids of varying size and shape were studied experimentally to systematically characterize the blast wave response. Approximately 100 lab-scale experiments were conducted in a homogeneous polymer with symmetric and non-symmetric cavity geometries. Polydimethylsiloxane (i.e., Sylgard) is used as a transparent solid material with a known principal Hugoniot and governing equation of state. Wave propagation were visualized with an optical density-

gradient based technique (Schlieren imaging) and imaged at 1 MHz. Blast waves (Mach ~ 1.5-2 in air) were created in the laboratory using exploding bridge wires. The surrogate seismic response at the surface generally followed intuitive and expected results. That is, larger cavities generally manifested smaller surface pressure peak magnitudes, reinforcing the concept of decoupling the chemical explosion from the solid medium. Further, asymmetric cavities can also reduce the propagating energy wave by introducing destructive reflecting waves in the cavity and at the boundaries of the polymer medium. Results may better inform models of energy transfer in situations where seismic waves pass through complex near-source and damaged regions.

Characterizing the January 2016 DPRK Nuclear Test Based on InSAR and FEM with Validation from Chemical Explosion SPE-6

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Fully-contained underground nuclear tests are likely the future of clandestine nuclear testing since they are more difficult to detect than those detonated surficially or in the atmosphere. It is therefore important to develop tools for relating surface-based observations to subsurface events that are not directly observable. Interferometric Synthetic Aperture Radar (InSAR) provides a way of measuring ground deformation caused by nuclear testing via a satellite remote sensing platform. We present a numerical model using the finite element method (FEM) to estimate the location and yield of underground explosions, constrained by surface deformation from InSAR data. This method provides an estimate that is independent from and complementary to the traditional seismic method. The model simulates the elastic deformation caused by an explosion and takes into account realistic topography, subsurface mechanical heterogeneity and effects from gravity. We use a multi-parameter search to estimate the cavity radius and depth then use those to calculate yield using an empirical scaling law. We estimate that the depth and yield of the January 2016 Democratic People's Republic of Korea (DPRK) nuclear test is 692-714 m and 4.19-8.07 kt, respectively, which is consistent with the seismic estimation. To validate our numerical model, we applied the same method to the sixth Source Physics Experiment (SPE-6) chemical explosion that was conducted at the Nevada National Security Site in 2016. Using LiDAR data covering SPE-6 that we obtained from Sandia National Laboratories, we verified that our method can reproduce the uplift/surface bulking observed in SPE-6 and provide accurate estimates of source depth and yield.

Denoising Seismic Signals Using Wavelet-transform-based Neural Networks

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In many cases, seismic waveform data recorded at stations can be thought of as a superposition of the signal from a source of interest and noise from various other sources. Frequency-based filtering methods of denoising recorded waveforms typically struggle in cases where the targeted signal and noise occupy similar frequency bands. Recently, techniques based on the use of deep learning convolutional neural networks (CNN), where a recorded waveform can be decomposed into its targeted signal and noise components, have led to improved results (e.g., Zhu et al., 2019; Tibi et al. 2021). These CNNs create signal and noise masks for the input waveform, which has been converted into the time-frequency domain using the short-time Fourier transform (STFT). The signal and noise components of the input waveform are then estimated by multiplying the CNN-generated signal and noise masks with the STFT of the input waveform and then converting each component back to the time domain. Advancements in the field of image denoising have shown the benefits of incorporating discrete wavelet transforms (DWTs) into CNN model architectures to create multi-level wavelet CNN (MWCNN) models, which allow for higher receptive field sizes while not sacrificing computational efficiency (e.g., Liu et al., 2018). Here, we utilize a data set of compiled signal and noise seismograms recorded by the University of Utah Seismograph Stations network to compare the performance of CNN and MWCNN denoising models. The models to be evaluated include CNN models utilizing the STFT and continuous wavelet transform of the waveforms as input data, and a MWCNN model, which incorporates the DWT into a contracting and up-sampling (U-Net) architecture. For each model, we examine the similarity of the recovered signal waveforms to the target waveforms from a test data set and present the improvements in signal-to-noise ratios (SNRs) achieved by each denoiser when compared to band-pass filtering on real world data.

Design and Testing of Discriminants for Local Seismic Events Recorded During the Redmond Salt Mine Monitoring Experiment in Utah

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The Redmond Salt Mine Monitoring Experiment in Utah was designed to record seismoacoustic data at distances less than 50 km for algorithm testing and development. During the experiment from October 2017 to July 2019, six broadband seismic stations were operating at a time, with three of them having fixed locations for the duration, while the three other stations were moved to different locations every one-and-half to two-and-half months. Redmond Salt Mine operations consist of night-time underground blasting several times per week. These blasts occur in a large underground tunnel complex, tens of miles long. Redmond Mine is located within a belt of active seismicity, allowing for easy comparison of natural and anthropogenic sources. Using the recorded dataset, we built 1373 events with magnitude (M_L) of -2.4 and lower to 3.3. For 284 of them, both the local magnitude (M_L) and coda duration magnitude (M_C) are well constrained. This subset consists of 75 blasts from the Redmond Salt Mine (RMEs), 206 tectonic earthquakes (EQs), and 3 blasts (QBs) from a mine located about 8 km from the Redmond Salt Mine. We used M_L - M_C, which is a depth discriminant, to successfully separate the population of mining blasts (RMEs plus QBs) from the group of earthquakes. The area under the receiver operating characteristic curve involving the RMEs and EQs is 0.98, and the optimum M_L - M_C cutoff -1.38. We are in the process of designing other discriminants that are effective at these local distances.

Enhancing Data Sets From Rudna Deep Copper Mine, SW Poland: Implications on Detailed Structural Resolution and Short-term Hazard Assessment

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Re-processing of seismological data with new methods of detecting and locating seismic events facilitates the enhancement of existing catalogs by orders of magnitude. This leads to unprecedented details in structural features and hazard assessment calculations. Here, we tested the software BackTrackBB (Poiata et al., 2016) on induced seismicity from Rudna Deep Copper Mine, SW Poland, using the data from the surface network LUMINEOS. Based on higher order statistics (HOS) and back-projection imaging we were able to increase the number of events in existing catalogs by about a factor 10.000. We incorporated all types of seismic events from magnitude M>3 mine collapses, recorded blasting work and detonations to machinery noise following our hypothesis that all event types contribute to seismic hazard in a mine.

In this study, we focus on the data from two days with major mine collapses: the 2016-11-29 Mw=3.4 and the 2018-09-15 Mw=3.7 events. The spatio-temporal distribution of seismicity of both days deciphered detailed horizontal and vertical structures and revealed the increase of seismic activity after the daily blasting work. The daily histograms exhibit similar patterns, suggesting the dominant influence of explosions on the overall seismicity in the mine. Using the enhanced data sets for short-term hazard assessment, we observed gaps in the activity rates before the main shocks. They were followed by sudden increase of seismicity, a simultaneous drop in seismic b-value, and an increase in exceedance probability for the assumed largest magnitude events. This demonstrates the usefulness of enhanced data sets from surface networks for revealing precursory phenomena before destructive mine collapses and suggests a testing strategy for early warning procedures.

Evaluating Spatio-temporal Trends in Infrasound Propagation Using Seismo-acoustic Arrivals From Repeating Explosions

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We analyze seismo-acoustic arrivals originating from weekly controlled munition disposals at the McAlester Army Ammunitions Plant (McAAP) in Oklahoma over a period of seven months during 2019. These arrivals were recorded across a combination of 121 temporary and permanently installed seismic stations across Oklahoma and the surrounding states. Arrivals were identified by a human analyst team as well as an automated noise-adaptive STA/LTA detector. Because of its consistency and duration, the McAAP dataset provides an opportunity to study the spatial and temporal variability of infrasound propagation as it relates to seasonally variable atmospheric conditions. Here, we present findings based on both the empirical waveform data as well as infrasound propagation modeling through Ground to Space (G2S) atmospheric specifications utilizing acoustic ray-tracing. We evaluate the utility of using acoustic arrivals recorded on seismic stations to characterize infrasound propagation. We study the discrepancies and similarities between the seismo-acoustic arrivals and the predicted ray tracing arrivals with the intention of evaluating spatio-temporal trends related to atmospheric dynamics. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

High Altitude Balloon-borne Acoustic Detection of the October 2020 Large Surface Explosion Coupling Experiment (LSECE)

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Impulsive atmospheric events, natural (e.g., lightning, meteors) or anthropogenic (e.g., explosions), can generate low frequency (f < 20 Hz) acoustic waves, also known as infrasound. Due to low attenuation at infrasonic frequencies, these waves can travel over very long distances and are thus suitable for studies of explosive phenomena, including the characterization and localization of such events. Typically, infrasound sensors are ground-based and stationary. However, in recent years, it has been demonstrated that high altitude balloons can serve as a platform for deploying infrasound sensor payload for the purpose of detection and source localization. One of the advantages of such platforms is relatively low local noise, allowing for better signal detection compared to surface-based sensors. Controlled explosion experiments provide important ground-truth data that can be utilized for the purpose of infrasound signal and source identification, and the development and improvement of detection and propagation algorithms. The Large Surface Explosion Coupling Experiment (LSECE), consisting of two one-ton (TNT equivalent; 1 TNT = 4.184 x 109 J) explosions, was performed at the Nevada National Security Site in October of 2020 with the aim to use all available sensing modalities (e.g., seismic, infrasound) to obtain well-characterized ground-truth data. The detonations occurred at the same location but two days apart, one in early morning and the other one in afternoon, in order to obtain ground-truth under different atmospheric conditions. Infrasound sensors carried by high altitude balloons detected the signals generated by the experiment. It was found that the local acoustic environment at these altitudes might be more complex than previously thought. We will discuss the propagation modeling results and the role of balloon-borne sensors in signal detection and geolocation. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Hydroacoustic and Seismoacoustic Responses of Explosions in Different Materials: A Parametric Study of Different Emplacements and Different Energy Depositions, and Comparisons With Experimental Data

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We have performed quasi-3D high-resolution numerical simulations of surface and underground explosions using LLNL's massively parallel eulerian hydrocode GEODYN to assess the impact of parameters such as yield, height of burst (HOB), depth of burst (DOB) and geological material on the resulting overpressure in air and seismic motions at distance. The material properties span a large spectrum from hard rock, such as granite with low porosity, limestone, sandstone, tuff, salt and very weak material, such as dry and wet alluvium, water and muds. Arrival times to surface station are determined by the shock wave propagation and the coupling of ground motion. We show that overpressures and peak velocities due to the same yield at the same scaled HOB/DOB are functionally very similar regardless the geological fabric and therefore the response can be scaled. Moreover, the impulse is calculated by integrating the initial positive pressure time-history. It was found that the functional form of the impulse as a function of scaled HOB/DOB is also consistent for emplacements above ground, at ground level and down to depths where cratering occurs regardless for all geological materials even though the material properties show drastic geomechanical variations. While the current study used numerical simulation from idealized blast and settings, additional factors can complicate observed seismic signals and bias the amplitudes and subsequent yield and HOB/DOB estimates. For example, we show that the emplacement lithology strongly impacts seismic amplitudes for deeply buried explosions. Furthermore, the behavior with HOB/DOB is different for the materials considered. Results are compared with legacy experimental data and the more recent forensic (LSECE) and proof-of-concept (MDE) surface explosions conducted at the Nevada National Security Site.

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Joint Yield Estimation by Local Seismoacoustic Observations from the 2020 Large Surface Explosion Coupling Experiment

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The Large Surface Explosion Coupling Experiment (LSECE) is a chemical explosion experiment conducted in Yucca Flat at the Nevada National Security Site (NNSS) in 2020. The main goal of the experiment was to provide the ground-truth data for acoustic and seismic wave coupling generated by large chemical explosions. The experiment consisted of two surface explosions of 1000 kg TNT equivalent. It is well known that there is a strong tradeoff in determining explosion yield and depth of burial simultaneously from either seismic or acoustic-only observations. Previous studies suggest that joint seismoacoustic analysis can resolve the tradeoff and reduce the uncertainty of yield and depth estimation dramatically. We demonstrate the capability of seismoacoustic analysis to improve the accuracy of explosion yield and depth estimation and quantify the uncertainty of estimates based on the accuracy of seismic and acoustic approaches. Particularly, local acoustic signal amplitudes can be substantially affected by weather conditions and LSECE including two detonations before dawn and after noon provide unique data to evaluate the model accuracy of acoustic wave propagation and seismoacoustic energy partitioning depending on local atmospheric conditions.

Numerical Modeling of Seismic Sources for Underground Explosions Within Jointed Rock

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Advances in numerical methods allow for the exploration of the effects of in-situ stresses in jointed media on seismic waveforms from underground explosions, manifested as the generation of SH and Love waves. Steedman et al. (2016) introduced a model where motions on jointed rock masses surrounding an explosion create shear waves, based on data from Phase I of the Source Physics Experiment (SPE; Snelson et al., 2013), which was carried out in a granitic pluton at the Nevada National Security Site. In this work, we present a numerical investigation which extends the rock joint domain to the entire 3D damaged region and study how motions on the joints change depending upon in-situ stresses.

Our study is focused on the fourth experiment in Phase I of SPE, SPE-4Prime. This experiment was an 89 kg TNT equivalent chemical explosion at a depth of 87.2m, which was overburied with a scaled-depth-of-burial of 1544 m/kt^(1/3) but for which Love waves were observed. The near-source calculations are done using the LANL hydrodynamic simulation code (HOSS), which combines finite-element based analysis of continua and discrete-element modeling, and it includes transient dynamics, contact detection, contact interaction and fracture solutions. The joints and surrounding material are modeled with continuum and/or discontinuum approaches. We look at the free-field motions, their transform into Reduced Displacement Potential, the elastic radius and prompt damage from the HOSS model. Our goals are to test how the 3D jointed model compares with the 2D model of Steedman et al. (2016) and to assess the influence of the in-situ stress, the structures and the material parameters of jointed media on the predictions. Our near-source results can be extended to surface sensors at larger observation distances thanks to a coupling interface to the seismic modeling code SPECFEM3D.

Numerical Simulation of High-frequency, Near-regional Seismic Phase Ratio Discriminants With Insights From the Source Physics Experiment

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High frequency (> 5 Hz) seismic phase ratios (Pg/Lg) are the basis for regional (> 100 km) explosion monitoring discrimination. The regional seismic crustal phases, Pg and Lg, are multiply reflected, scattered phases that interact with the variable crustal waveguide with random heterogeneity and topography at high frequency. Simulating the seismic wavefield with scattering, crustal heterogeneity and topography at this distance and frequency is computationally expensive and has not been performed to date. We present the results from numerical simulations of explosions and earthquakes related to the Source Physics Experiment (SPE). The SPE is composed of a series of chemical explosions located at the Nevada National Security Site and is designed to improve our understanding and modeling capabilities of explosion sources. The numerical simulations in this work offer a predictive model for explosion and earthquake regional seismic phase ratios. The predictions are compared with observations from the explosions and earthquakes related to SPE.

Regional Long-period Moment Tensor Analysis of Mining Events and Potential mb-Ms Explosion Screening False Alarms

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Routine mining events present a potential for false alarms in seismic event screening for explosions based on a criterion that uses the difference between body and surface wave magnitudes (mb-Ms). We have compiled a collection of seismic events in several mining regions including 11 seismic events (2012-2017) at the Rudna mine in Poland, a 2020 mine collapse at the Kiruna mine in Sweden, 10 seismic events (2005-2019) in the mining regions of South Africa, a 2021 collapse at Crab Orchard Mine in Tennessee, a 1995 mine collapse at Solvay mine in Trona, Wyoming, the 1995 Solikamsk-2 mine collapse in Russia and the 2007 Crandell Canyon mine collapse in Utah. As an example, we computed regional-distance long-period moment tensor (MT) solutions for 10 seismic events in the Witwatersrand Basin gold mining region near Orkney, South Africa using a calibrated 1D regional Earth velocity model (Xie et al., 1996). This model predicts displacements from earthquakes out to distances of 1000 km and frequencies up to 0.1 Hz. This calibrated model was used to compute Green's functions to estimate full MTs of these 10 seismic events. Six of the nine full-MT solutions exhibited closing crack collapse type mechanisms in source-type plots based on the MT eigenvalues (Hudson et al., 1996; Ford et al., 2010). Using a mb-Ms screening criterion (e.g., Fisk et al., 2002; Selby, 2012; Ford and Walter, 2014), only 1 of 6 closing crack type MT events screened as an explosion. A 26 km deep normal-faulting earthquake also nearly screened as an explosion. The Kiruna mine collapse also would have not produced a false alarm. These mining events provide an opportunity to further explore the discrimination outcomes from using Magnitude Distance Amplitude Corrected (MDAC) P-to-S regional phase ratios and coda amplitude envelope methods compared to their regional MT solutions and mb-Ms event screening. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-829821.

Source Analysis of the 1993 Rock Valley Earthquake, Southern Nevada

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A sequence of shallow earthquakes occurred in 1993 within the Rock Valley Fault Zone, located in the southern part of the Nevada National Security Site (NNSS). The largest earthquake was an M_W 3.7 event that occurred on 05/30/1993. A temporary seismic network deployment confirms that more than 600 earthquakes occurred over the following months. In this study, we revisit the source parameter estimates of this reported seismicity. Our efforts focus on the main event and larger earthquakes of this sequence using local to regional seismic observations. We resolve seismic moment, orientation and source depths using a combination of regional moment tensor analysis and first motions. This work is part of a multi-institutional effort to characterize this tectonic activity for a planned chemical explosion that will be co-located with one of the earthquakes in the sequence, as part of Phase III of the Source Physics Experiment (SPE). Because this phase of SPE requires accurate source depth estimates of previous seismicity, we emphasize the comparison of our solutions to hypocenters reported in previous studies. We also focus on the seismic moment of the mainshock and its uncertainties, which becomes important for studying explosive yield estimation and calibration of the planned chemical explosions.

Using Deep Learning to Develop a High Resolution Planetary Boundary Layer Model for Infrasound Propagation

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Previous research has shown the utility of deep learning in predicting atmospheric structure for regional infrasound propagation. A Long-Short Term Memory network can be used to predict temperature, wind speed and wind direction up to altitudes of ~40 km with performance equal to or better than state-of-the-art reanalysis models. However, these regional models do not resolve the planetary boundary layer (PBL), the lowermost part of the atmosphere, well. An accurate model of the PBL is important at local distances for acoustic waveform modeling. This is often accomplished by using a suite of robust and expensive meteorological sensors. A method to predict atmospheric structure at this resolution would be very beneficial for low yield monitoring scenarios where the ability to field sensors is limited or the timing of the event is not known beforehand. Here we show a high resolution PBL model developed via deep learning techniques using an ambient urban infrasound data set coupled with weather measurements in Las Vegas, Nevada, USA. Results show the ability to use a data-driven method to predict, interpolate and extrapolate an atmospheric model that can be used in acoustic waveform modeling.

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Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes

Oral Session · Friday 22 April · 4:30 PM Pacific

Conveners: Weston Thelen, U.S. Geological Survey (wthelen@usgs.gov); Amanda Thomas, University of Oregon (amthomas@uoregon.edu); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); Barrett Johnson, University of Washington (bnjo@uw.edu); Seth Moran, U.S. Geological Survey (smoran@usgs.gov)

Deep-learning-based Earthquake Catalog Production at Axial Seamount From 2014 to 2021

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Axial Seamount is an active submarine volcano on the Juan de Fuca Ridge. It's most recent eruption in April 2015 was captured by a cabled, 7-station ocean bottom seismometer (OBS) array in real-time. High-precision earthquake locations, computed in real-time from double-difference analysis of kurtosis picks and cross-correlation delay times (http://ddrt.ldeo.columbia.edu/Axial), image fine-scale seismicity that improves our understanding of Axial's complex ring-fault system and its dynamic behavior. A remaining challenge in our processing workflow is improving detection capability, especially during periods of intense seismic activity and high oceanic noise levels (e.g., whale calls, storms). In this study we built a machine-learning earthquake catalog from continuous recordings over 7 years. We use PhaseNet, a deep-learning phase picker to detect and pick phase arrivals from continuous data, and GaMMA, a machine-learning associator to associate the picks. The associated events are located with Hypoinverse and NonLinLoc using a 3-D velocity model and finally relocated with HypoDD using cross-correlation delay times. We show that PhaseNet, originally trained on California earthquakes, performs well with OBS recordings without retraining. We evaluate the pick uncertainty against cross-correlation delay times and find that their accuracy are comparable to current kurtosis picks used in production. We demonstrate that the new workflow is robust to various oceanic noise sources and explosive acoustic signals that hamper detections in the current catalog. We also show that the GaMMA associator efficiently separates events close in time, which is critical for seismic monitoring during eruptions. The new machine-learning earthquake catalog enables us to determine detailed fault structures in- and outside the caldera and better monitors complex fault activation processes as they evolve in real-time. These results and the underlying workflow show great potential for cloud-based operation which will facilitate high-resolution real-time monitoring of earthquakes, especially in regions with high seismicity rate.

Hydroacoustic Investigation of Lava-water Interactions During the 2018 Kilauea Eruption

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The growth of volcanic islands and the stability of their flanks is largely dependent on coastal and submarine volcanic processes, which are not well understood or easily observed. Lava typically enters the ocean in one of two primary ways: explosive or passive. Explosive lava-water interactions violently break the lava into many fragments and ash. Passive ocean entries include the formation of pillow lavas and the emplacement of offshore lava flows. These larger "lobes" of cooling lava may form more stable flanks, relative to those composed of primarily fragmental material (from explosive interactions).

During the 2018 Kilauea volcano eruption, over half of the total erupted lava was emplaced offshore. The different types of lava-water interactions can be studied via data from a network of 12 ocean bottom seismometers (OBS) and hydrophones deployed offshore of Kilauea during the eruption (between July 11 and September 16, 2018). Although significant activity is recorded on the hydroacoustic network, when lava is flowing into the ocean, little correlation is observed between specific explosive events at the coastline and signals recorded by the hydrophones. Acoustic ray tracing using Bellhop (Porter, 2011) shows that coastal signals are poorly recorded by hydrophone deployed at depth; signals are most clearly recorded when the source is located >400 m offshore. We conclude that the most common lava-water interactions successfully recorded were associated with lava flows on the submarine flank. These data provide insight not only into the submarine activity of the lava flow, but also into the utility of hydroacoustic data in studying volcano evolution with possible implications relating to flank stability.

Low-frequency Seismicity Registered at Ceboruco Volcano, Mexico

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The magma and related hydrothermal fluid movement and their interaction with solid rock in active volcanic regions generate a wide variety of seismic waves whose characterization can mitigate the risk of a potential eruption. In the western region of the Trans-Mexican Volcanic Belt, the Ceboruco

Volcano, considered to be one of the most hazardous volcanoes in Mexico, is located and whose last eruptive period was 1870-1875. To establish the current state of the Ceboruco Volcano, a detailed study of the seismicity in the surroundings of the volcanic edifice has been carried out. The deployment of a dense temporary seismic network with 25 seismic stations in an area of 16 km x 16 km from November 2016 to July 2017, as part of the P-24 project of the CeMIEGeo consortium, has allowed the detection of a total of 81 earthquakes concentrated beneath the crater with depths between 4 and 8 km. In this study, it is observed that the recorded low-frequency and hybrid seismicity occurs in swarms, and we specifically identify four sequences that have been characterized in detail with the determination of the first focal mechanisms available for this volcano.

Our results suggest a change in the local seismicity distribution compared to earlier observations, which reported seismic activity near the volcano edifice associated with fluid migration along zones of weakness related to the extensional stresses of the Tepic-Zacoalco rift. The changes in seismic patterns and obtained focal mechanisms are consistent with observed fluid effects at many geothermal sites worldwide, but also could suggest resumption of activity at this currently dormant volcano.

Recent Eruptive Activity of Sangay Volcano Observed by an Infrasound Array

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Sangay is one of the most active volcanoes around the world. Since May 2019, it started a period of more intense activity with occasional ash falls that have affected farms, crops and important Ecuadorian cities. Since 2013 this volcano has been monitored by a single multi-parametric station, called SAGA, with seismic, infrasound and SO2 sensors alongside a time-lapse camera. SAGA is located at the foot of Sangay's SW flank. Due to its proximity and the preferential wind direction, this station has been affected by ash covering its solar panels.

Since October 13th, 2021, the eruptive activity of Sangay volcano has been recorded, analyzed and interpreted also using an infrasound array, named SAG1. This array is composed of five Chaparral Model 64, VX-2 elements with a 120-sec Trillium compact seismic sensor and a Nanometrics 6-channel Centaur CTR4-6S digitizer. This instrumentation was kindly provided by VDAP-USGS to the Instituto Geofisico (IGEPN) for volcano monitoring purposes. This array was installed above a small hill in the forested plain southeast of Sangay, 34 km away due to due to lack of access to this remote volcano. Elements form a polygon with distances between 31 to 34 m away from a central node. Data is transmitted in real time to the IGEPN headquarters where it is automatically processed using Ipensive software. Despite the array location, it is able to record episodes of

Sangay's strombolian activity with amplitudes below 0.1 Pa and frequent small vulcanian explosions with amplitudes above 0.5 Pa. A drumbeat sequence and a succeeding large ash emission that occurred on Dec. 2nd, 2021 were detected simultaneously by SAG1 and SAGA stations. SAG1 array has also detected explosions from Reventador volcano, located 227 km and a completely different azimuth.

Matched Filter Detection of Lava Lake Seismicity Using a Dense Short Period Network on Mount Erebus Volcano

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Erebus volcano on Ross Island, Antarctica has maintained an erupting phonolitic lava lake for at least five decades. During active periods, the lava lake hosts large (up to ~10-m diameter) gas slugs rising through the conduit that create impulsive Strombolian eruptions and produce very long period (VLP) signals on broadband seismograms. We combine near-summit broadband observations and reanalyze data from a 100-station three-component short-period (4.5 Hz) network deployed in an approximately 3 by 3 km region around the main crater of Erebus Volcano during December 2008. Lava lake eruption template events are identified from broadband seismograms from their characteristic and repeating VLP spectral signature of nonharmonic modes between 0.033 and 0.2 Hz. Multi-channel and multi-station waveform matched filter correlations are performed across the short-period network using template events and correlation values that are three or more standard deviations are extracted into a working inner crater event catalogue, yielding several thousand event detections over 19 days. While some of the signals in this catalogue are unique, some "families" of repeating lava lake events can also be identified through similar waveforms, which are further interpreted by trends in location, occurrence and spectra. We observe time-varying non-Poissonian interevent times and an approximately power-law size-frequency distribution with an excess of small events. Investigating the various event families that transpire in the inner crater region contributes to improved characterization and understanding of the seismogenic behavior of the lava lake degassing system and assists in the creation of a workflow that can be applied in volcanic and other circumstances that generate prolific low-level impulsive seismicity.

Advances in the Use of Seismic and Acoustic Methods to Constrain Physical Processes at Volcanoes

Poster Session · Friday 22 April · Conveners: Weston Thelen, U.S. Geological Survey (wthelen@usgs.gov); Amanda Thomas, University of Oregon (amthomas@uoregon.edu); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); Barrett Johnson, University of Washington (bnjo@uw.edu); Seth Moran, U.S. Geological Survey (smoran@usgs.gov)

A Compact Digital Broadband Seismometer for Permanent and Temporary Volcano Monitoring: Güralp Certimus

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Seismicity is an an important part of volcano monitoring strategies across the globe. Seismic data from volcanic regions provides researchers with insights into the link between sub surface processes and seismicity, directly feeding back into improved monitoring and hazard assessment. Improved seismic monitoring systems that are lower power, easier to deploy and more cost effective can drive the move toward denser seismic monitoring arrays, like those outlined by the SZ4D initiative, which can more accurately characterize observed activity over time.

Güralp has addressed this issue with a sensor technology with the ability to function at any angle, without the need for a gimbal system or human interference. The Certimus broadband digital seismometer combines compact a form factor with OBS-inspired low power usage to provide the operator with easily deployable stations. An omnidirectional sensor allows the operator to install the system without levelling and without needing to intervene if the system changes orientation during deployment, e.g. during ground inflation or deflation.

A user-configurable long-period corner between 120s and 1s allows the operator to select the instrument response most suitable for the application and also eliminated the need for extensive instrument pools. All configurations can be managed on an optional hardened touchscreen locally or remotely through the web interface of the on-board Minimus digitizer. The large 64GB internal microSD cards also means that the system is well suited for offline rapid deployments.

This highly versatile and configurable sensor technology will play an important role in delivering reliable seismic data from dynamic volcanic environments, by ultimately bringing down the costs of regular sensor maintenance by reducing the need for regular sensor alignment. In addition, rapid deployment pools of seismic sensors can be streamlined as the Certimus is capable of displaying various frequency responses.

Advancing Eruption Research Through an Updated Monitoring Network at Semisopochnoi Volcano

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Analyses of large seismo-acoustic datasets of volcanic explosions from monitoring networks are often considered problematic for research due to sparse station coverage and issues with data quality and continuity. The main explosive phase of the ongoing phreatomagmatic eruption of Semisopochnoi volcano, Alaska began shortly after a complete upgrade of the monitoring network in 2021 that now comprises six broadband seismometers, three broadband infrasound sensors and two web cameras. The new network is capturing an unprecedented, high-quality record of the eruption that we are using to investigate explosion source processes and the evolving configuration and state of the magmatic system as the eruption progresses. An explosion catalog is being generated through a novel implementation of the REDPy repeating event detector code on the infrasound network. The catalog contains over 800 events to date, providing a rich research dataset to study the relationships between explosion earthquakes and infrasound. Initial results from the catalog indicate a high degree of similarity in the infrasound waveforms with only one dominant family occurring since explosions began in July 2021. We also explore the magnitude-frequency distribution of the explosion earthquakes for insights into the eruption dynamics of the ash-rich explosions. The eruption has now spanned summer and winter months in Alaska, exposing the network to major seasonal changes in weather conditions. This allows us to determine the effects of changing temperature and wind speed and direction, on recorded infrasound amplitude distributions across the network, as well as how changing noise levels affect signal detection capabilities. This work highlights the potential of modern monitoring networks to produce research-grade data, even at remote volcanoes, which aids in advancing our knowledge by diversifying the types and styles of eruptions observed globally.

Attenuation of Seismic Waves Beneath the Krýsuvík Volcanic System, Reykjanes Peninsula, South-West Iceland

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The 2021 Fagradalsfjall eruption on Reykjanes peninsula (SW Iceland) was preceded by high levels of seismic activity from December 2019 to 19 March 2021, covering the entire peninsula. At the beginning it was not clear if an eruption would occur nor which volcanic system would then erupt. The last eruption on the peninsula occurred ~800 years ago. The Krýsuvík volcanic system, about 16 km east of Fagradalsfjall, was one of the areas experiencing intense seismicity. Krýsuvík is known for its seismic velocity anomaly, tectonic earthquakes and the occurrence of very shallow microearthquakes (Kristjánsdóttir, 2013). Moreover, there are indications of magmatic infiltration near 10 km depth, which will need further investigation (Hobé et al. 2021).

We used the seismic activity from December 2019 to October 2020 (more than 4 months before the 2021 Fagradalsfjall eruption) to study attenuation of seismic waves. We selected 650 earthquakes with high quality seismograms in the magnitude range from 1 to 4, in the depth interval 1 - 7 km. These earthquakes were recorded by the local seismic network REYKJANET. The special robust technique of "double peaks" for automatic determination of P- and S-wave amplitudes was developed and tested. These amplitudes were used to determine average values of quality factors Qp and Qs for the whole area covered by REYKJANET and the upper crust down to depth of 10 km, which is covered by seismic rays. Moreover, local anomalies of the attenuation were detected for some small parts of the crust. The most pronounced anomaly was found beneath the Krýsuvík volcanic system for both, P-waves and S-waves. In recent days (end of December 2021) an intensive seismic swarm was registered close to Krýsuvík volcanic system. This has been interpreted as triggered earthquakes due to the uplift at Fagradalsfjall caused by dike injection. Currently, there are no signs of an uplift in the Krýsuvík area.

Crumbling Volcanoes: A Summer of Debris Flows in the Cascades

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Energetic mass flows, including debris flows and lahars, occur frequently in volcanic environments due to strong topographic gradients with seasonal snowpack and glacial cover on heterogeneous, hydrothermally altered and weakly consolidated slopes. On quiescent volcanoes, the primary driver of debris flows is the ingress of water. The unusually warm summer of 2021 caused significant melting of snow and ice that contributed to at least 26 debris flows at Mount Shasta, California, whereas rainfall contributed to nine flows at Mount St. Helens, Washington. The emergent, long-duration seismic signals associated with these events were primarily observed on relatively sparse networks designed for routine volcanic monitoring, allowing limited and delayed detection during daily analyst checks. We supplemented the existing networks with additional temporary, non-telemetered instrumentation: nodal seismometer and acoustic microphone arrays at Mount St. Helens recorded several debris flows and a nodal seismometer array and camera deployment at Mount Shasta recorded simultaneous debris flows in multiple drainages. The number of events and variety of observations available provide an opportunity to test algorithms for the detection of debris flows. We focus on retrospective time-series analyses and amplitude-based locations, as well as analyses of improvements in network sensitivity with additional instrumentation. Where possible, we incorporate non-seismic observations (e.g., satellite imagery, ground-based reports of flows) for drainage verification. Knowledge gained from these analyses will inform development of rapid, automated characterization of debris flows at these and other Cascade volcanoes.

Determining Ash-rich vs. Vapor-rich Explosions Using Continuous Infrasound at Volcán De Fuego

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Infrasound is used as a tool to detect and monitor unrest at volcanoes around the world and is fundamental in detecting and characterizing explosive activity. Volcán de Fuego in Guatemala is particularly amenable for infrasound monitoring given its open-vent activity, frequent explosions (several per hour) and high-intensity infrasound signals, which can be recorded at distances of more than ten kilometers from the summit. Since 2018, Guatemala's Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH) has maintained at least three telemetered infrasound stations around Volcán de Fuego as a fundamental surveillance tool. During this period of time, tens of thousands of explosions have been recorded.

Between 14 May and 30 August, 2021 the INSIVUMEH monitoring network was supplemented with a seasonal deployment of infrasound sensors, including a high quality, low-noise station situated approximately 5 km from the summit. Continuous records permit robust statistical analysis of the discrete explosions including features in both time and spectral domains. This study applies both unsupervised and supervised machine learning to the 2021 data to optimize feature selection to classify explosion signals as ash-rich or vapor-rich. This analysis is intended to complement explosion detection and provide information about ash content which impacts local communities.

Earthquake Sequences of the 2018 Kīlauea Volcano Eruption

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The 2018 Kīlauea volcano eruption produced unprecedented levels of seismicity in the volcano's instrumented history. The Hawaiian Volcano Observatory (HVO) documented over 60,000 earthquakes during the eruption, a rate that was approximately 20 times higher than normal. Network detection capability was saturated, resulting in catalog magnitude of completeness degradation from M1.4 before the eruption to M2.8 during the eruption. Here, we present spatiotemporal patterns of seismicity from the HVO earthquake catalog and related observations during three main seismic sequences during the eruption. The first sequence marked an intrusion of magma following the collapse of Pu'u ʻŌʻō cone and opening of eruptive fissures in the lower East Rift Zone, over 20 km away. We use the rate of earthquake propagation energy release to estimate strain release associated with the first two phases of the eruption. Second was a vigorous aftershock sequence following the magnitude-6.9 earthquake at 22:32 UTC on 4 May 2018. We compute *p*-value for the sequence and its triggered seismicity, which spanned an extensive offshore area. The third and most productive sequence consisted of 62 complete and one partial episode of stepwise caldera collapse at the Kīlauea summit between 17 May and 2 August. Each near-daily (~30 hour) cycle of seismicity and deformation brought thousands of small earthquakes and culminated with a relatively large ~Mw5 very long-period (VLP) earthquake. We show patterns of observables such as seismicity rate, seismic amplitude, and moment release throughout these cycles, relating them to spatiotemporal phases of the volcano's caldera collapse.

Fundamental and First Higher Mode Rayleigh Wave Ambient Noise Tomography on the Island of Hawaii

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The ambient noise cross-correlation is a powerful tool to extract the Empirical Green's Functions (EGFs) in many geological settings, including volcanoes, making it useful for exploring the volcano structures and monitoring eruptions. To date, the published studies have documented successfully extracted fundamental-mode Rayleigh waves, but few higher mode has been reported in volcanic settings. In fact, the overtones were robustly extracted only in certain cases, for example, in sedimentary basins and in the oceans.

Here we present the multi-component EGFs extracted on the Island of Hawaii, where both fundamental and first overtone Rayleigh waves are observed. Because of the large lateral structure variations, the observed ambient noise field is complex. To deal with the complexity of the wavefield, we developed a workflow to automatically extract the dispersion of the two different modes in the frequency range of 0.1 to 0.6 Hz. The fundamental and first overtone Rayleigh waves have different ellipticity, which is used to separate the two modes. Then, the group velocities are picked as the dispersion curve closest to the 1D model predictions. The resulting group velocities are used to produce a filter to clean the waveform. The final group arrival is picked on the cleaned waveform as the arrival time of the maximum energy. Using the measured group velocities, we solve for the group velocity maps. The inverted results match well with the geological features on the surface.

Our study demonstrates that the higher mode Rayleigh wave can provide valuable constraints that are complementary to those of the fundamental mode in a volcanic setting. Together the bi-mode Rayleigh wave group dispersions could be used to better understand the near surface volcano structures and dynamics.

Identifying Lava Bombs in Seismometer Data During the 2018 Kilauea Eruption

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Where and when did the relevant Kilauea eruptions occur? What are lava bombs? Why are we studying their seismic and acoustic signals? What data are we using? What are our results? What do we want to achieve?

The big island of Hawaiʻi is home to one of the most active volcanoes in the world, the Kilauea shield volcano, which has been erupting continuously since the 1980s. In 2018, the Kilauea volcano erupted and caused severe damage to surrounding properties and infrastructure. The molten lava flows also created dangerous explosions of solidified lava where they reached the ocean, caused by steam generated by the immense heat. Known as lava bombs, these phenomena have already injured people, presenting a clear hazard.

Lava bombs may also be potentially used as sound sources to calculate travel times in the ocean; and studying their waveform signals may help in studying past Kilauea ocean entries and lava bench collapses.

A new catalog of lava bomb estimations was created after data was collected from the Kilauea South Flank (KSF) network of ocean-bottom seismometers that were deployed after the 2018 eruption. We study lava bombs' seismic and acoustic signals using land seismometers in local land networks to identify lava bombs as loud and sudden events.

In sampling the land data, we identify moderate- to high-intensity, short-duration, broadband signals, similar to the signals found in the KSF hydrophone waveforms. These signals correlate with theoretical travel times as both seismic signals and as acoustic signals.

We aim to apply a short-term average/long-term average (STA/LTA) detection process to the land data to automate detection of lava bomb events, to help refine and confirm the lava bombs catalog and to make the process broadly applicable and replicable. This will help in further studying the 2018 Kilauea eruption, as well as other coastal volcanic processes such as lava bench collapses and submarine landslides

Numerical Simulation of Flow, Transport of Heat and Chemical Transport Processes in Volcanic Chambers Partially Filled With Molten Rock and Consequence on Dynamic Seismo-acoustic Signatures

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A transient numerical study of conjugate flow, heat and mass transfer by natural convection of gases—air, carbon dioxide, noble gases—within an underground cavity partially filled with molten rock is presented. The molten rock is initially considered to be at rest at an initial temperature and concentration. The molten rock is viscous and possesses strength that is temperature, viscosity and crystal fraction dependent. Under natural conditions, convection cells are developed within the molten rock leading to circulation, mixing and degassing of the initially trapped gases. Furthermore, the molten rock as well the degassing enhances the conjugate convection flow in the air gap above the molten rock within the cavity and promote Bénard-Rayleigh-Taylor instabilities. We illustrate the onset of the different regimes of instabilities and their combined effect of flow, heat and mass transport of different gas species as function of the geometry of the cavity and the fraction of molten rock. The transient governing equations of mass, momentum, heat and chemical species were solved using the finite element method. Several numerical coupling schemes are presented and numerical stability conditions are illustrated. We also present a sensitivity analysis of the effect of the outer cavity boundary condition on the heat loss and cooling to the adjacent rock formation and its effect on the convective mixing topology with the air gap and the molten rock. We present four- and three-dimensional synthetic sesimo-acoustic wave signatures generated on the dynamic time series of the evolving physicochemical processes in the chamber while assessing the interplay between frequencies of interest, material uncertainty and significance of key the physical phenomena.

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The Internal Structure of Öraefajökull, Iceland Imaged by Local Earthquake Tomography

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Öraefajökull located along the southeastern most coast of Iceland is the tallest (2110 m) volcano in the country. Vatnajökull, a massive ice sheet over 8000 km^2 in size with a volume of about 3000 km^3 completely covers Öraefajökull making the volcano difficult to study. Additionally, Öraefajökull last erupted in 1727 and has shown little to no signs of erupting until recently, which

could pose a large threat not only to Iceland but all of Europe as well due to the potential of a large explosive eruption. Between 2017-2019 seismicity increased from about five earthquakes with magnitudes greater than 1.5 to over 4000 per year. The increased seismic activity at Öraefajökull allowed for the use of local earthquake (LE) tomography to yield vital information about the relatively unknow internal structure of the volcano. The LE tomography uses P- and S-wave arrival times to simultaneously solve for earthquake locations and the velocities of the subsurface using 17 three component seismic stations installed on and around Öraefajökull. Results of the LE tomography show a network of centralized earthquake locations, ranging between the surface to about 8 km depth directly beneath the central caldera. P/ S wave velocity ratios depict a high velocity zone near the surface, an anomaly of high V_p/V_s ratios in a low velocity zone ranging between 2-7 km depth and a higher velocity/low V_p/V_s region below 7 km directly under the caldera. The structural interpretation of the LE tomography imaging at Öraefajökull below the caldera may be hypothesized as intrusive bodies (<2 km), a melt or mush zone (2-7 km) and the presence of cumulates (>7 km).

Time-lapse Seismic Velocity Changes Coincident With Dome Emplacement at Great Sitkin Volcano, Alaska

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Ambient noise seismic methods are advantageous for volcano monitoring during relatively quiet time periods, for example when ocean-generated noise dominates over any continuous volcanic seismicity such as tremor. Great Sitkin Volcano in Alaska began an effusive dome-building eruption in late July 2021 that was characterized by low levels of seismicity. This effusive phase followed a Vulcanian explosion on May 26, 2021 and, by the beginning of 2022, had produced a lava dome at the summit of the volcano with a volume of approximately 30 million cubic meters. The 2021 eruption was preceded by years of elevated earthquake activity at the volcano.

We observe a clear increase in relative seismic velocity on the order of 0.5% coincident with the extrusion of the dome at Great Sitkin. Comparable velocity changes have been associated with domes at other volcanoes such as Merapi (velocity increase during dome growth) and Montserrat (velocity decrease after dome destruction). We detect the velocity increase at Great Sitkin using coda wave interferometry applied to ambient noise correlations in the 0.5-2 Hz frequency band using 4 broadband seismic stations located on the slopes of the volcano. The 4 seismic stations yield 10 total correlations for analysis: 6 cross-correlations and 4 auto-correlations. By applying a tomographic method to spatially localize the lateral location of the velocity changes, we find the area of largest change is not centered on the volcano's summit; it instead lies roughly 3-4 km to the northwest. This part of the volcano consists of a geologically recent (< 10,000 years old) caldera structure interpreted to have formed from large-scale edifice failure toward the northwest. We hypothesize that the shallow subsurface (< 2 km depth) on this northwestern side of Great Sitkin is weaker and has a relatively higher velocity susceptibility to the applied stress caused by the weight of the dome and subsidence of the volcano.

Understanding the Interplay Between the Volcanic and Tectonic Processes at Mount Hood

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The faults to the south of Mount Hood produce the highest seismicity rates in Oregon, though it is still unclear why. Since permanent seismic monitoring began in 1980, ~3000 earthquakes have been recorded at Mount Hood, the majority of which occurred in short-duration swarms, each producing between 20 and 200 earthquakes. The seismicity at Mount Hood can be grouped into two categories: Summit seismicity and Off-summit seismicity. Most of the earthquakes belong to the latter and include the largest recorded events (M4.0 in 1974, M4.5 in 2002 and M4.0 in 2021). Detailed analysis of the off-summit seismicity by Jones and Malone (2005) suggests earthquakes occur on faults to the southeast. In the last 20 years, the number of earthquakes recorded at Mount Hood has doubled and, more interestingly, starting in 2010 the area immediately west of the summit became seismically active. With the recent improvements to the seismic network, Mount Hood has one of the best networks of Cascade Range volcanoes. However, because of the swarm-like seismicity, many low-magnitude earthquakes are obscured and cannot be located through standard location procedures. Using the methods of matched-filter earthquake detection and relative relocation, we set out to build a more complete catalog of Mount Hood seismicity. With our high-resolution catalog, we hope to gain insights into the subsurface volcanic and regional tectonic processes that control seismicity, build intuition about the relationship between the hypocenters and adjacent faults and more accurately map the complex stress field surrounding Mount Hood.

It's Baaaaack. Uplift and Seismicity Near South Sister, Oregon

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Beginning in early to mid 2020, deformation rates near the Three Sisters Volcanic Cluster in central Oregon increased from those seen in the prior decade. InSAR and GNSS measurements independently confirmed the deformation, located approximately 5 km southwest of South Sister. The centroid and rate of deformation are similar to deformation that occurred in the mid-1990s and are inferred to result from intrusion of magma at ~6 km depth. In response to the recent deformation and minor shallow seismicity, the USGS released an Information Statement on January 31, 2022. Styles of volcanism in this region are variable, ranging from mafic cinder cones and shield volcanoes to rhyolitic domes. The most recent eruptions in the area were rhyolitic in composition and occurred near South Sister 2.2 and 2.0 ka. Overall, earthquake activity has been modest since the densification of the seismic network in the early 2000s, mostly consisting of a swarm of earthquakes extending from the deformation area toward Middle Sister in 2004. Since then, sporadic earthquakes have been spread above the deforming area, but at rates of less than 15 earthquakes per year according to the published catalog by the Pacific Northwest Seismic Network. Since the increase in deformation in 2020, there have been several small swarms of earthquakes, mostly too small to locate and thus not well represented in the published catalog. In this presentation, we will summarize the 2020-present deformation and accompanying earthquake activity, along with evidence supporting magma intrusion as a likely explanation for the 1990s-present uplift.

Advancing Multi-scale Evaluations of Seismic Attenuation

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Annabel Haendel, GFZ Potsdam (ahaendel@gfz-potsdam.de); Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Fabrice Cotton, GFZ Potsdam (fcotton@gfz-potsdam.de)

Some Remarks on Seismic Attenuation in Shallow Geological Layers

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Seismic attenuation and the associated quality factor (*Q*) have been extensively studied within various disciplines, ranging from observational and engineering seismology to near-surface geophysics and soil/rock dynamics with a particular emphasis on geotechnical earthquake engineering. Within the broader framework of seismic site characterization, various experimental techniques have been adopted over the years to estimate the near-surface shear-wave quality factor (*QS*). In this presentation, a review of what *Q* is will be presented and, in particular, the phenomena associated with the high-frequency shear-wave attenuation factor (kappa) and its relation to *Q* are summarized.

This review will show that while the effect of the apparent attenuation can be reliably estimated, the distinction between intrinsic and transmission (i.e., reflection, refraction and scattering) effects still requires further dedicated efforts. This becomes an issue of major importance when empirically estimated *Q* values are used in numerical simulations of ground motion or site response. In fact, substituting the intrinsic quality factor with an apparent one (which includes all components, hence, potentially leading to double counting) might strongly affect the amplitude and duration of the obtained time series with the obvious impact on downstream calculations. Caution is recommended when using *Q* values estimated with techniques intended for specific purposes that are not intended for estimating *Q*. Furthermore, the frequency range used for *Q* estimation and the strain level exerted on the material–both in the laboratory and in the field–should always be considered.

The Good, the Bad and the Ugly: Investigating Bias in High-frequency Attenuation Using Noise Modeling

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The high-frequency attenuation parameter, kappa, is measured on the Fourier amplitude spectrum of recorded ground motions. There are several methods to perform this task, including band-limited ones focusing on the spectral slope and broadband ones inverting several seismic parameters. What they all have in common, however, is that the user must select the frequency band in which to apply them, considering criteria among which a judgment as to signal quality. This is typically done (if at all) by estimating a signal-to-noise ratio (SNR), selecting a threshold and excluding frequencies where the noise is strong. This typically penalizes higher frequencies. In the work at hand, we use the recent technique proposed by Pikoulis et al. (2020), which stochastically models the noise spectrum with the aim of improving the signal spectrum and rendering it usable at higher frequencies. We demonstrate the discrepancy between the traditional (noise-avoiding) and new (noise-modeling) technique on recorded data and on simulated data. By modeling rather than avoiding the noise, we can achieve a more robust estimate of kappa by using data down to around SNR=1, demonstrating the underestimation typically due to the noise. Some of our method's advatnages are that we do not need to rely on any particular theoretical model or assumption, and that it is even possible to go beyond conventional 'well-behaved' noise models to more unfavorable conditions such as spectral peaks, etc.

Time-dependencies of κ

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κ describes the attenuation due to regional and local geological conditions. It is usually split into a path component κR, that is dependent on the regional quality factor Q, and a site component κ0. κ0 is used in e.g. the host-to-target adjustment of ground-motion models (GMPEs), in synthetic ground-motion simulations, as predictor variable in GMPEs and for site effect adjustment. Despite its widespread use, it is known that κ shows large within-station variability that can be even larger than the between-station variability of sites located on different geology. The observed within-station variability of κ is usually attributed to ground-motion directionality or the influence of the event focal depths. Also dataset choices and the record and spectrum processing can affect the κ estimation.

In this study, we show additionally that some of the within-station variability of κ is caused by temporal variations. We use sites from the Japanese Kik-net database with hundreds of recordings to study the time dependence of κ at the surface and at depth. We first observe that e.g. sensor re-installations affect the estimate of κ as has been reported by other authors before. Furthermore, we show that κ decreases during strong shaking (large PGA) at some sites and may follow a recovery curve after large earthquakes. Also the regional path component κR, that is usually assumed to be constant, shows some variation over time. Finally, one site undergoes strong seasonal variations leading to differences in κ of up to 30 ms between summer and winter. All of these examples show that κ is influenced by even more factors than so far known.

The Variation of Kappa With Induced Shear Strain and the Accuracy of High Frequency Components of Site Response Analyses

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This study examines earthquake motions from two soft soil sites to investigate empirically the influence of soil nonlinearity on the high-frequency spectral decay parameter, κ_o. Site response analyses indicate that κ_o should increase with increasing induced shear strain due to the larger damping associated with soil nonlinearity. Recent studies, however, have shown that κ_o for large intensity motions remains at its small-strain value, which is consistent with small-strain damping. To further investigate this behavior, two soft soil sites in California (Westmorland - Fire Station with Vs30 = 194 m/s and El Centro Array #11 - McCabe School with Vs30 = 196 m/s) are selected for analysis. These sites have each recorded more than 70 motions and these motions span a significant range of intensities with PGA between 0.003 and 0.6 g and PGV between 0.16 and 63 cm/s. The κ for each motion was computed using the slope of the acceleration Fourier Amplitude Spectrum and corrected to κ_o based on the site-to-source distance. The induced shear strain for each motion was estimated from the ratio of PGV to Vs30, and for the two sites the induced shear strains range from about 0.001% to 0.3%. Across this strain range, the data do not show any systematic change in κ_o as the induced shear strain increases, with the κ_o values remaining similar to the small-strain values (small-strain κ_o = 0.040 s for Westmorland - Fire Station and κ_o = 0.062 s for El Centro Array #11 - McCabe School). These results reinforce the findings of recent studies that showed that soil nonlinearity and the associated increase in damping does not increase κ_o and thus the strain-compatible damping used in site response analyses may not accurately represent the high-frequency components of ground motion for large intensity motions.

What Does Kappa Mean in Nonlinear Site Response Analyses?

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Soil nonlinearity is commonly triggered at softer sites subjected to strong ground shaking. Previous work by the authors has shown that the high-frequency spectral decay parameter kappa can be affected by soil nonlinear behavior and that the influence is station-dependent. Large deformations associated with the onset of soil nonlinear behavior lead to a reduction in shear modulus and an increase in material damping ratio. Meanwhile, multiple cycles of shearing within soil layers for high-frequency and short wavelength seismic waves allows more attenuation to take place, which hints a potential relationship between kappa and soil dynamic properties beyond the linear-elastic regime. Additionally, recent studies have highlighted the role of high-frequency amplifications on kappa (e.g., particularly in negative kappa values observed in a given record), which means kappa may reflect the combined effect of damping and amplification in the high-frequency range. This work investigates the correlation between kappa and soil dynamic properties (e.g., material damping ratio) with the increasing shear strains. One-dimensional, fully nonlinear, total stress site response analysis is performed. Multiple site conditions (e.g., multiple layers vs. single layer to test contributions of scattering to kappa, changing confining stresses and soil types to see differences in kappa due to anelasticity, etc.) are simulated and their influence on kappa values per record and site-specific kappa is quantified. Nonlinear site response analyses are also conducted at three KiK-net stations, where soil nonlinearity affects significantly kappa estimates as shown by the authors on previous studies. The resulting site-to-site variability (e.g., the correlation between site specific kappa0 and Vs30) further advances our understanding of which site conditions may require adjusted kappa values to account for the effect of the onset of nonlinear soil behavior.

Observation and Model of Scattering Attenuation of 500 +- 200 Hz Induced Seismic Emissions

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We report on observations and modeling of scattering attenuation of high frequency emissions induced by a 5-6 km deep hydraulic stimulation in crystalline basement rock. Our study took place during an Engineered Geothermal System development project near Helsinki. Our data were recorded by (1) a 12-level array of borehole seismometers at 1.9 to 2.4 km depth immediately above the stimulation well and (2) a 12-station network of shallower (0.35-1.1 km) borehole seismographs. Array and network sensors were located in the same basement rock as the stimulation well. We suggest that the 200 to 800 Hz high-frequency emissions recorded by the array resulted from variable slips on permeability-related fractures in these rocks. The basement rock causes negligible anelastic attenuation (Q ~ 3000). Instead, by the time the emissions reach the deep and shallow sensors, 90% of their high-frequency energy has been scattered into long trains of coda waves.

The amplitudes of these codas decline as hyperbolic functions of observation time t, as given by H(t) ~ 1/(a+bt)1/b, 1 < b < 2. Numerical 3D acoustic wave scattering replicates these decline profiles due to scattering by spatially correlated wave speed fluctuations consistent with crustal porosity spatial fluctuations. The spatially power spectrum of these fluctuations is given by the power law 1/k, where k is their wavenumber length scale—forms of randomness generally known as a pink noise distributions of correlated spatial fluctuations. This same pink noise distribution is observed in well logs of the properties of fractured rock, including sonic, resistivity, gamma and geochemical logs. Interpreting these properties as the direct result of fluid flow in the fracture themselves, we suggest that the observed coda wave scattered/delayed seismic energy might be playing a role in forming the maps of fluid pathways created with ambient seismic imagining methods.

Geometric Spreading and Apparent Anelastic Attenuation of Response Spectral Accelerations

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Approaches to modeling geometric spreading and apparent attenuation of 5%-damped spectral accelerations differ significantly between developers of the GMPEs. In recent NGA-West GMPEs geometric attenuation is usually determined empirically and assumed to be magnitude dependent. Since geometric attenuation and apparent (anelastic) attenuation are interdependent it results in significant differences in modeling SA attenuation. I am discussing apparent anelastic (combination of intrinsic and scattering) attenuation of 5% damped response spectral accelerations (SA) associated with the geometric spreading of surface waves. In contrast to the "seismological" *Q(f)* factor measured using Fourier spectra of *S*-, *Lg*- or coda-waves SA quality factor Q_{SA}(f) represents apparent attenuation of response spectral accelerations. In the recent ground motion prediction equations (GMPE) models for the stable continental regions (SCR) (Graizer, 2017) and active crustal regions (ACR) (Graizer, 2018) I assumed large distance geometric spreading of SA to be of the order of *Ggeom~R-05*. Multiple inversions performed to estimate *Qsa(f)* demonstrated the best fit to be *Q(f)=120f^0.96* for the ACR for frequencies between 0.1 and 100 Hz and the best fit to be *Q(f)=186f^0.99* for the SCR for frequencies between 0.1 and 40 Hz. Apparent attenuation was found to be magnitude dependent with Q_{SA} factor increasing with magnitude. Resulting apparent attenuations of response spectral amplitudes at rupture distances of more than 50 km for the ACR and more than 70 km for the SCR are practically linearly dependent upon frequency demonstrating significantly different behavior compared to the "seismological" *Q*-factor. Considering that seismological quality factor *Q* is usually determined using *S*-, *Lg*- or coda-waves not necessarily responsible for the SA attenuation they may not be used in GMPEs.

Uppermost Mantle Pn-wave Attenuation in the Anatolian Plateau and Surrounding Regions

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The Anatolian plateau is situated in the central part of Alpine-Himalayan orogenic belt and formed at the terminal stage of the Wilson cycle, a period marked the termination of oceanic subduction and conversion to continental collision (Burke, 2011). Violent interactions between mantle and overlying crust, such as slab segmentation, upwelling of asthenosphere and lithospheric dripping, are invoked to explain the late-Cenozoic magmatisms and uplift of the entire Anatolian plateau (Gall et al., 2021; Göğüş et al., 2017; Schildgen et al., 2014). Seismic Pn-wave is usually the first arrival in regional seismograms and less affected by crustal structures or contaminated by other phases. Therefore, Pn-wave attenuation can be useful for characterizing the properties of uppermost mantle and investigating the crust-mantle interactions. By combining the single-station and two-station spectral data and using the method by Zhao et al. (2015), the upper mantle Pn-wave attenuation tomography is conducted for the Anatolia plateau and surrounding regions. The resulted broadband Pn attenuation model is composed of distributions between 1.0 and 10.0 Hz. They reveal strong lateral variations of attenuation across broad regions, especially from east to central Anatolia, despite large variations among different frequencies. This may be explained as the tectonic environment shifted from post-collision in the east to oceanic subduction in the west. Widespread low anomalies in the east Anatolia may be resulted from the break-off of the Btilis slab. Small patches of low anomalies in the central Anatolia may be related to lithospheric dripping and upper mantle upwelling through gaps between segmented slabs. This research is supported by the National Natural Science Foundation of China (41630210, 41974054, 41974061 and U2139206).

Tasman Line in Eastern Australia Constrained by Regional Lg-wave Q Tomography

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Following the breakup of the Pangaea, the Australia, broken from Antarctica at ~34 Ma and continually migrated northeastward at a speed of 6-7 centimeters per year, is the largest independent island and the smallest continental plate on the Earth. Undergoing complex volcanic activities and tectonic evolution since the Archaeozoic, the Australian continent can be characterized by stable cratons in the west and orogenic movements and volcanic activities in the east. The north-south line to divide the west and east tectonics is termed the Tasman line, a boundary between the ancient and newborn lands in today's Australia. The Tasman line is not only associated with continental lysis, but also an important symbol of the break-up of the Rodinian supercontinent. However, there still exist some uncertainties as to its nature of the transition and many conflicting interpretations due to various data based analyses. In this study, we trace the Tasman line based on a fine scale crustal attenuation structure obtained by using regional Lg-wave Q tomography. The resolution reaches 1° × 1° in most Australian continent. Significant variations are observed in Lg-wave attenuations from west to east, and the Q distributions are correlated well with the geological features in Australia. The cratons in southwestern, northern and central parts of Australia often have higher Q values with their Q0 (Q at 1.0 Hz) values range between 1000 and 2000, whereas the volcanic regions, sedimentary basins and orogenic areas in eastern Australia are characterized by increased attenuations with their Q0 values ranging from 100 to 800. The Tasman line, constrained by using Lg-wave Q gradient in this study, can provide some new constraints for understanding continental evolution in the Australia. This research was supported by the National Natural Science Foundation of China (41974061, 41630210, 41974054, and U2139206).

Lateral Variations of Crustal Lg-wave Attenuation in and Around the Scandinavian Peninsula

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Seismic Lg wave is the guided shear wave propagated in the crust. Typically, it is sensitive to the sudden change of the waveguide structure, the attenuation and scattering in the crust (Bouchon, 1982). The passive continental margin on the west of Scandinavia is composed of crust transition from oceanic to continental. Lateral variations of the Lg attenuation can be observed in areas where crust thickness changes from the continental margin to continent (Zhang and Lay, 1995). To investigate the lateral heterogeneity of the crust, we analyze the propagation characteristics of Lg waves by conducting the Lg wave Q tomography (Zhao et al., 2010) in the Scandinavian Peninsula and surrounding regions. A total of 37,735 vertical-component broadband digital seismograms was used to create a dataset which is larger and more updated than those previously used in this region (Demuth et al., 2019; Kvamme et al., 1995). The dataset is composed of seismograms from 449 earthquakes recorded by 863 stations, mostly from the Norwegian National and GEOFON Seismic Network during the period between 1992 and 2021. A broadband Lg-wave Q model between 0.05 and10.0 Hz was constructed for this region. The resolution reaches approximately 1.0°×1.0° within frequency band between 0.5 and 2.0 Hz in this region. Prominent lateral variations of Q values at various frequencies were observed, with the high-Q values in the continental area and moderately high Q values in the offshore passive margin of the Scandinavian Peninsula, probably owing to both the changes of crust thickness and overlying thick sediments. The relatively low Q values in the North Sea Basin presented strong attenuation, presumably because the covered sediments and the developed graben structure hindered the propagation of the Lg wave. In the southeast Scandinavian Peninsula, the Baltic Shield, a large stable crust segment composed of very old, crystalline metamorphic rocks, is characterized by weak attenuation (Ostrovsky, 1999; Roland et al., 1993). This research was supported by the National Natural Science Foundation of China (41974061, 41974054, 41630210, and U2139206).

Advancing Multi-scale Evaluations of Seismic Attenuation

Poster Session · Wednesday 20 April · Conveners: Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Annabel Haendel, GFZ Potsdam (ahaendel@gfz-potsdam.de); Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Fabrice Cotton, GFZ Potsdam (fcotton@gfz-potsdam.de)

Computing Path Effects of a Large Magnitude Event From Path Effects of Many Small Magnitude Events on the Same Rupture Plane

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During the development of most Ground Motion Models (GMMs), the path effects from one event to one site are assigned to a single path between one point (e.g., the closest point along the fault, hypocenter) and a site, regardless of the magnitude of the event. When the seismic hazards of future large magnitude earthquakes are considered, their path effects are assumed to be the same as for small magnitude events with the same path. Considering that seismic waves travel from any point along the rupture planes that extend hundreds of kilometers for large magnitude earthquakes to a site, the single travel path assumption for large magnitude earthquakes is largely inappropriate which can lead to inaccurate seismic hazard assessments. This is especially important as non-ergodic GMMs are trying to separate source, path and site effects. To properly quantify the path, we would theoretically need to include all possible paths from points across the entire rupture plane to the site. In this study, we propose to investigate the quantitative relationship between the path effects of a large magnitude event and that of many smaller ones on the same rupture plane, using numerical ground motion simulations.

Our initial study involves a rupture along the San Andreas Fault simulated in CyberShake studies. The rupture plane has a length of 490 km and width of 24 km. In CyberShake simulations, the entire fault plane can be covered by one M8.05 rupture, three M7.55 ruptures, five M7.35 ruptures, ten M7.05 ruptures and 25 M6.55 ruptures. We compute and compare the average path effects among the five different magnitude groups. The correlation coefficients between two magnitude groups decrease with the increasing magnitude differences. Correlations of path effects among M6.55, M7.05, M7.35 and M7.55 ruptures are generally good (CC>0.7), but the correlation drops to around 0.5 when the M8.05 rupture is considered. We present results from the CyberShake analysis and a preview of results for a new targeted simulation study developed to better address this issue.

Examining Temporal Variations in Coda Q Attenuation Before and After Some Significant Canadian Earthquakes: The 2017 Resolute Earthquake (Mw 6.1) in Nunavut, Canada

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Several recent studies around the world show temporal variations in coda Q attenuation before and after significant earthquakes. In this study, we examine potential temporal changes in coda *Q* values for a number of significant Canadian earthquakes in different tectonic environments, including the 2017 M6.1 Resolute earthquake along the northern margin and the M7.8 Haida Gwaii subduction earthquake on Canada's west coast.

We calculate coda Q attenuation values before and after the January 8, 2017 Mw 6.1 Resolute earthquake, 8° north of the Arctic circle in Nunavut, on the basis of the Aki's single backscattering model. Waveforms from 100 earthquakes ($2.0 \le M \le 4.6$) in almost 24 years before the mainshock and 66 events (mainly aftershocks) in about 4 years after the mainshock recorded by the only nearby seismic station of the Canadian National Seismic Network (CNSN) were utilized. Based on our analysis, overall average of Q_0 (*Q* at 1 Hz) decreased from 89 (before the mainshock) to 83. The most significant decrease in the frequency range between 2 and 16 Hz is observed for areas corresponding to ellipse parameter a_2 of 50, 70 and 80 mainly related to aftershock activity. Precursory *Q* changes were not detectable before the mainshock due to the lack of reported seismicity within 100 km of the recording seismic station for almost 2 years from April 2015 to January 2017. These results are in agreement with other global studies that show a decrease in Q_0 following a major earthquake, likely the result of increased fracturing and fluids.

Including Radiation Pattern Effects in Ground-motion Models for Taiwan

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Most ground-motion models (GMMs) parameterize the earthquake source by three parameters: magnitude, style-of-faulting, and source depth. The GMMs are isotropic in terms of the source scaling for these three parameters. The radiation pattern, which leads to azimuthally varying source effects, is not included in most GMMs. As a result, any systematic radiation pattern effects are treated as aleatory variability in the path terms in the GMMs which does not make physical sense. We incorporate the far-field radiation pattern into GMMs for pseudo-spectral-acceleration (PSA) and Fourier-amplitude-spectra (FAS) GMMs for the Taiwan region. A key issue is how to combine the radiation pattern from the SH and SV components for predicting the RotD50 amplitudes of the ground motion used in GMMs. A suite of point-source numerical simulations was generated for a range of focal mechanisms and site azimuths. An empirical model for the phase differences between the radial and transverse components was developed using Taiwan ground-motions for use in the simulations. The results show that vector sum of the SH and SV far-field radiation patterns, Fs, has a higher correlation with the RotD50 amplitudes of the ground motion than the arithmetic sum or the geometric mean. The radiation pattern term is modeled by S0(M) + S1(M) ln(Fs + S2) in which S0(M), and S1(M) are linear functions of magnitude between M4 and M6; they equal 0 for M>6. The magnitude dependence reflects that, for large-magnitudes and short distances, the ground motion at a given rupture distance is more affected by the slip distribution and rupture timing than by the average radiation pattern from the subevents along the rupture, but the radiation pattern is seen for small magnitude events, particularly at long periods. The S1(M) slope is similar for PSA and FAS at long periods (T>0.5 sec) with a value of about 0.6 for small magnitudes. At short periods (T<0.2 sec), the slope is slightly larger for PSA than for FAS. The results are similar using radiation patterns computed for 1-D and 3-D velocity models.

Pn-wave Attenuation Structure of the Uppermost Mantle Beneath the Japan Sea

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The Pacific lithosphere subducted into the deep mantle and drove the opening of the Japan Sea as a back-arc basin. The subduction rollback produced thermal heterogeneities in the mantle, which can be effectively constrained by seismic wave attenuation. To understand the opening mechanism of the Japan Sea and the evolution of the back-arc basin, we conduct the 1°×1° high-resolution broadband Pn attenuation tomography to constrain the upper mantle thermal structure beneath the Japan Sea and its surrounding areas. The upper mantle under the intraplate volcanoes, certain area in the back-arc basin and the Japan Arc are characterized by strong Pn attenuations. Our results, along with previous studies in this region, suggest that, beneath Northeast China, the asthenosphere upwelling may have been separated into multiple magma branches to feed volcanoes in Changbaishan, Jingpohu and Chuga-Ryong regions. Two strong Pn attenuation anomalies are observed beneath the Japan Sea. Alongside with the Pn velocity anisotropy, they suggest two possible regional mantle flows escaped eastward from Northeast China under the driving force of the divergent rollback of the subducting Philippine Sea and Pacific slabs. During Miocene and Pliocene, the southwestern part of the Japan Arc rotated clockwise and the northeastern part rotated counterclockwise around separate rotating poles. The stretch of the divergent rollback and the push of the suggested mantle flows may drive the "double-door" opening of the Japan Sea with similar rotation angles. At the same time, the distribution of low beneath the back-arc basin suggests that the heating and intrusion of the mantle material thickened the back-arc crusts in the Tsushima Basin and the northwestern edge of the Japan Basin. This research was supported by the National Natural Science Foundation of China (41674060, 41630210, 41974054, 41974061, and U2139206).

Spatial Variability of the Spectral Decay Parameter Kappa and Near-source Attenuation in Central Italy

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We investigate the spatial variability of the average spectral decay parameter κ by determining the variation of κ with hypocenter distance r (κ_{av} (r)) within four quadrants that divide the Central Italy region, taking as a reference axis the Apennines chain orientation. We found higher values of κ_{av} (r) in the southern quadrants, where seismicity and faulting are more active, and less attenuation in the more geological stable NE quadrant. We computed κ using *S*-wave recordings from the Central Italy dense seismic array. The data set used consists of 266 earthquakes, 353 stations and 13,952 observations of κ with a mean value of 0.0412 ± 0.0177 within the distance range between 7.1 and 168.8 km. We model the variation of κ with hypocenter distance r as $\kappa(r,\kappa_0,\kappa_s)=\kappa_0+\kappa_s+\kappa_{av}$ (r), where κ_0 and κ_s represent the near-site and the near-source decay parameters, respectively, and κ_{av} (r) the average κ along the *S*-wave source-station paths. We first determine κ_{av} (r) with a nonparametric inversion approach and then we solved for κ_0 and κ_s with a second inversion. Preliminary results show that κ_{av} *(r)* increases with distance within the whole distance range analyzed (9.2-80.6 km). The near-source decay parameter takes values in the range $0.0 < \kappa_s \leq 0.026$ with a mean value of 0.003 ± 0.006, which represents 7.5% of the mean value of the observed κ. The values of the near-site decay parameter vary in the range $0.0035 \leq \kappa_0 \leq 0.0823$ with a mean value of 0.0298 ± 0.0133 that is 72% of the mean value of the κ observed. We conclude that most of the high-frequency attenuation takes place near the site, since κ_{av} (r) contributes with only 20% of the spectral decay.

Spatiotemporal Variation of Stress Drop for the 2019 ML 6.0 Changning Earthquakes and Its Aftershock Sequence in the southern Sichuan Basin, China

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The stress drop is one of the fundamental parameters for predicting the ground motion and measuring the stress release generated by an earthquake (e.g., Sheareret *al.*, 2006, Oth, 2013). To obtain the source excitation spectrum of an earthquake and use it to estimate the stress drop, commonly used is the empirical Green's function method, which deconvolves the observed spectrum with the spectra of nearby small events. This process removes the propagation effect and site response from the observed spectrum to obtain the source excitation spectrum (e.g., Hough, 1997, Abercrombie, 2014). Instead, when the high-resolution broadband regional attenuation model is available, the attenuation effect along the propagation path can be directly calculated and removed from the observed spectra, similar to calculating the magnitude (Zhaoet *al.*, 2017, Nuttli, 1986). The Lg-wave, traveling in the continental crust, is one of the most prominent regional seismic phases, is less sensitive to source radiation patterns and often serves as a robust signal to measure source parameters, such as the scaler seismic moment and corner frequency (e.g., Campillo, 1990, Ottemoller, 2003). Here, we retrieve the Lg-wave source excitation spectra for the June 17, 2019 Changning earthquake and its aftershocks between 0.05 and 10.0 Hz based on a high-resolution broadband Lg-wave attenuation model by Zhao *et al.*(2013). Our results show that the stress drops are rather scattered for this earthquake sequence, ranging from 0.08 MPa to 32 MPa with a median value of 0.6 MPa. Spatiotemporal variations of stress drops reflect fault properties and its stress release process. Since the Changning earthquake and its aftershock zone are very close to the local salt mines, where a large volume of water has been injected to the subsurface for decades. This earthquake sequence is likely influenced by the water injection and diffusion. This research is supported by China earthquake science experimental field (2019CESE0103, 2018 CESE 0102, 2016 CESE 0203) and National Natural Science Foundation of China (41974054,42104055, 41974061, 41630210, and U2139206).

The Eastward Expansion of the Eastern Tibetan Plateau Inferred From Stress Drops of the 2021 Ms 6.4 Yangbi Earthquake in Yunnan and the Ms 7.4 Maduo Earthquake in Qinghai, China

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On 21 May 2021, the M_S 6.4 Yangbi earthquake in Yunnan province and the M_S 7.4 Maduo earthquake in Qinghai province occurred consecutively within ~4.3 hours in the eastern Tibetan Plateau. According to the alignment of regional fault systems and their earthquake mechanisms, both earthquakes were likely related to the lateral expansion of the eastern Tibetan Plateau. In this study, the stress drops of the Yangbi and Maduo earthquake sequences are estimated from Lg-wave spectra for all M_L>3.0 earthquakes. The observed spectral data are corrected for the path attenuation and site effects based on a broadband Lg wave attenuation model and the site response database in east Tibetan Plateau. In both sequences, rapid decreases of stress drops were observed immediately after mainshocks, indicating abrupt stress releases by mainshocks. The relatively high stress drops observed from Yangbi foreshocks may suggest stress accumulation in the fault system. We refine the spatial distribution of stress drop for both Yangbi and Maduo sequences using *HypoDD*. The results demonstrate that high stress drop can be found where the orientations of seismogenic faults changed. In particular, high stress drops in the Yangbi sequence could also be associated with several earthquake clusters that were distributed roughly perpendicular to the strike of main fault, suggesting stress concentration at intersections between the main fault and secondary fault system. The complicated pattern of stress drop for the Yangbi sequence might result from significant rotation of the Chuandian block in southeastern Tibet. In contrast, the seismogenic fault system for Maduo sequence are probably smoothed and hotter due to relatively faster eastward movement of the Bayan Har block, resulting in relatively lower stress drop for the Maduo aftershocks. This research was supported by the National Natural Science Foundation of China (42104055, U2139206, 41974054) and the China Seismic Experimental Site (2019CSES0103).

Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone

Oral Session · Thursday 21 April · 8:00 AM Pacific

Conveners: Jason R. Patton, California Geological Survey (jason.patton@humboldt.edu); Lori A. Dengler, Humboldt State University (lori.dengler@humboldt.edu); Peggy Hellweg, University of California, Berkeley (peggy@seismo.berkeley.edu); Bob McPherson, Humboldt State University (robert.mcpherson@humboldt.edu); Rick I. Wilson, California Geological Survey (rick.wilson@conservation.ca.gov)

The Role of Geosciences in Informing the Seismic Risk Management of the Pacific Gas and Electric Humboldt Bay Power Plant, Humboldt County, California

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The shutdown of one of the first U.S. commercial nuclear reactors at Pacific Gas and Electric Company's (PG&E's) Humboldt Bay Power Plant (HBPP-Unit 3) is a valuable case history on the role the geoscience community has played informing the risk-management of critical infrastructure. HBPP was constructed from 1956 to 1963 in the pre-plate tectonic era of geoscientific understanding. Unit 3 operated commercially from 1963 to 1976 before it was shut down for seismic retrofit and refueling following the 1975 M5.6 Fortuna earthquake and the discovery of an exposure of the Little Salmon fault by geologists within a mile of the HBPP. PG&E implemented an intensive inves-

tigation of faults in the region using seismic geology, age dating and geophysics and confirmed that the Little Salmon fault was an active reverse fault that dipped beneath the plant site. Geologic investigations extended into the early 1980's and contributed to the 1983 decision to decommission the plant. Other geologic investigations in Washington and Oregon during the 1980's established that the Cascadia Subduction Zone was active, extended into northern California, and was connected to the Little Salmon fault at the southern end of the subduction zone. Although the Unit 3 was shut down in 1976, spent fuel rods from the plant required onsite storage in an Independent Spent Fuel Storage Installation (ISFSI). PG&E developed specific models of the Little Salmon fault zone during the 1990's to estimate the coseismic uplift/subsidence at and near the plant from Cascadia earthquakes as well as the tsunami potential at the ISFSI site. In the 2000s, the site was assessed for long-term sea level rise, tectonic uplift/subsidence, and the combined effects of continued tectonic deformation and climate change. While the plant site was restored and officially decommissioned in 2021, the ISFSI remains on site until a permanent federal repository is made available to accept the spent fuel.

Interseismic Fault Loading in California's North Coast Constrained by Geodetic Data

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The forearc of the southern Cascadia subduction zone, just north of the Mendocino triple junction, is home to a sequence of quaternary-active crustal faults that accumulate strain due to the interaction of the North America, Juan de Fuca/Gorda and Pacific plates. revious estimates suggest that these faults accommodate a third of the plate convergence rate in the region. These faults, including the Little Salmon and Mad River fault zones, are located near the most populated parts of California's North Coast and show paleoseismic evidence for meter-scale slip events in the past few thousand years. However, the present-day geodetic slip rates of these faults are poorly constrained. In this work we analyze a compilation of interseismic geodetic velocities from GNSS, leveling and tide gage data to constrain slip rates on the upper plate faults near the Mendocino triple junction. We construct Green's functions for steady-state interseismic strain accumulation (i.e., backslip) for faults embedded in a thin elastic plate over a viscoelastic mantle of very high viscosity, equivalent to assuming that the mantle relaxation time is long compared to the earthquake recurrence interval. We then use a constrained, non-negative inversion technique to determine best-fitting slip rates on the major faults and we investigate slip rate tradeoffs between faults. Initial results indicate that the Little Salmon fault system is an important part of the slip budget in this area. Our work has implications for slip partitioning in oblique subduction settings and for the quantification of seismic hazard in the southern Cascadia forearc.

Characterizing Active Cross-shore Faults Along the Continental Shelf in Southern Cascadia

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We integrate new high-resolution multi-channel sparker (MCS) and chirp seismic imagery, targeted sediment coring, relocated seismicity and legacy seismic data to map and characterize active cross-shore faults in southern Cascadia. Co-located MCS and chirp seismic profiles collected along and across the shelf between the Eel and Rogue rivers in 2018 and 2019 reveal active folding and faulting within the shallow subsurface along the offshore extensions of the Table Bluff, Little Salmon, Mad River, Bald Mountain-Big Lagoon and Lost Man fault zones. MCS data image locally folded and faulted Neogene and younger strata to sub-seafloor depths > 500 m and provide structural context for the chirp imagery that offer higher resolution (10's of cm) imagery in the shallower (< 50 m) subsurface. We use stratal geometry on cross-shelf chirp profiles to identify and map the regional transgressive surface that records erosion from sea level rise following the Last Glacial Maximum (LGM, ~21 ka-present) to use as a strain marker for characterizing cross-shore fault deformation. Relief along the transgressive surface is evident by both long-wavelength (10's of km) features that likely reflect active folding and punctuated vertical offset ranging from 5 to 10 m coincident with fault traces of the Table Bluff, Mad River, Bald Mountain-Big Lagoon, and Lost Man fault zones imaged in MCS and chirp seismic data. Similarly, cross-sections of relocated seismicity reveal steeply dipping lineations of events associated with the Table Bluff and Little Salmon faults. Transgressive surface ages at depths between 50 and 100m below sea level are estimated to be between 11 and 15ka, based on sea level curves, which result in maximum vertical deformation rates of between ~0.3 to 0.9 mm/yr. These rates are less than those estimated on land and potentially reflect a change from compressional to transpressional tectonics across the shoreline as these faults die off or bend to the north along the shelfbreak.

Plate Torture: The Gorda Deformation Zone

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The Gorda Deformation Zone, the southernmost fragment of the larger Juan de Fuca plate system, is a highly deformed tectonic accommodation zone, allowing the surrounding larger plates to act in a more rigid fashion. Numerous interpretations of its deformation are extant, the most recent model is as an asymmetrical flexural-slip buckle with a vertical axis, utilizing reactivation of spreading-ridge fabric normal faults as strike-slip faults. Second-generation faults and reactivated rift-propagators crosscut the inherited structural grain. This model suggests that spreading-rate variations along the Gorda Ridge may be controlled by internal deformation of the plate rather than the reverse, as previously hypothesized. Southern Cascadia is strongly influenced by the subduction of rift propagator wakes (RPW) which are more extensive than previously realized, both in lateral extent and in topographic expression. The sub-surface expression includes not only tall seamounts, but deep holes as deep as 2.0 seconds TWT, or about 1800m. While a typical expression includes vertical features of 300-500m, in some cases as much as 1600m of basement topography is observed. The modern positions of the RPW may be consistent with paleoseismic segmentation proposed using onshore and offshore paleoseismic data. Southern Cascadia upper plate deformation includes a strong transition from outboard mixed-vergence compression, to inboard transpressive deformation. It also includes an anomalous region of listric normal faulting and subsidence which could be related to this transition, or some other origin. Offshore paleoseismic records include beds from full and segmented subduction events, as well as historic smaller earthquakes from the NSAF (1906, 1700) and Petrolia 1992. These observations serve to validate submarine paleoseismology in this difficult region with multiple fault sources, as well as address the possible stress-triggering relationship between Cascadia and the NSAF.

Sources of North Coast Seismicity Revisited: Tectonics, Moment Tensors and Finite Fault Models for the Gorda—Southern Cascadia Region

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Thirty years ago, "Sources of North Coast Seismicity" (California Geology 1992 V45 pp40-53) gave an overview of the seismicity of California and the adjacent offshore area from the vicinity of the Mendocino triple junction north to the Oregon border. Since that publication, the 1992 Cape Mendocino earthquake sequence occurred and seismic instrumentation monitoring in the region has improved. Applying tools such as NLL-SSST-coherence to relocate and visualize the seismicity in the region highlights the structure of the Mendocino Fault, as well as other interesting features, such as events both in and below the oceanic crust and within the continental crust. High-quality broadband data have allowed the determination of moment tensors for more than 340 earthquakes starting in 1992, ranging in moment magnitude from M_w 3.2 to 7.2, and located between 122.4°W and 126°W and 40.0°N to 42.0°N. Very few of these quakes have thrust mechanisms indicating they are on the subduction interface. The vast majority of the events have strike-slip mechanisms. Those along the Mendocino Fault have E-W/N-S trending fault planes. The mechanisms of the earthquakes along the fractures within the Gorda plate are consistent with the trends of those fractures, oriented primarily NE-SW/NW-SE. For several large earthquakes since 2000, including 2010, 2014 and most recently the event in Dec 2021, finite fault (FF) solutions have been prepared using broadband, strong motion and GNSS data. For offshore earthquakes in the Gorda plate, the FF planes that best fits the data trend NE-SW. The 1992 paper suggested that the region hosts five areas that are

sources of damaging earthquakes, the Gorda plate, the Mendocino fault, the San Andreas transform system, the North American plate and the Cascadia subduction interface. The seismicity and moment tensor data illuminate those five source areas and also suggest that the area around the Mendocino triple junction be considered a sixth distinct zone.

The 1992 Cape Mendocino Earthquake: A Turning Point in US Tsunami Hazard Mitigation

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The April 1992 M7.2 Cape Mendocino earthquake was the first recent earthquake to produce a local tsunami on the US West Coast. Recorded on 13 tide gauges in Oregon, California and Hawaii, eyewitness reports suggest that it reached heights of a meter. No tsunami bulletin was issued after the '92 earthquake. No post tsunami field investigation was conducted as the first International Tsunami Survey Team (ITST) would not launch until the Nicaragua tsunami later the same year. The tsunami caused no damage but marked a sea change in awareness of near-source tsunamis and in US national tsunami hazard mitigation efforts. The '92 tsunami sparked interest in the scientific and emergency management communities leading to workshops on US tsunami readiness under the auspices of the Senate Appropriations Committee. In 1996, the US National Tsunami Hazard Mitigation Program (NTHMP) was created based on workshop recommendations. Concern in California over a larger earthquake led to a planning scenario for an M8.5 earthquake and tsunami on the Gorda segment of the Cascadia subduction zone. The scenario included the first publicly distributed tsunami hazard map for the Cascadia region. Another outcome was creation of the CGS/CalOES California Tsunami Program. Since then, interest in tsunamis soared with events in the Indian Ocean, Chile and Japan. NOAA deployed the DART network of 39 seafloor bottom pressure sensing instruments. With precomputed tsunami models for all parts of the Pacific, DART data are now an essential part of the tsunami warning system. All US coastal states and territories are members of the NTHMP with 194 jurisdictions recognized as TsunamiReady communities. Challenges remain with different approaches to hazard assessment and risk communication among West Coast states. And, as always, the time elapsed since a damaging tsunami, pandemic constraints and disaster fatigue pose additional "attention span" hurdles to agency tsunami support and public awareness.

Block Models of the Southern Cascadia Forearc Based on Geodetic Data

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Crustal faults in the southern Cascadia forearc help to accommodate strains related to subduction and the northern San Andreas fault system. However, the interseismic slip rate on several of these major fault systems, including the Mad River fault zone (MRFZ), Little Salmon fault and Grogan fault, are not well constrained. Paleoseismic work reveals that the Little Salmon fault and MRFZ have hosted multiple earthquakes in the past few thousand years, and regional strain rate maps confirm that all of these faults are actively accommodating deformation in the forearc. Therefore, constraining the slip rate and sense of slip on these faults is crucial for evaluating regional seismic hazards and for gaining a better understanding of how crustal strain is accommodated near the Mendocino triple junction. This work focuses on using elastic block models to investigate the overall nature of these three fault systems and to explore how each fault contributes to deformation in the forearc. We test eight different block geometries to explore various forearc fault configurations and analyze the partitioning of strain. We also include the Cascadia megathrust to account for tradeoffs between subduction and crustal thrusts and to test different locking scenarios. Block rotation, internal strain and interseismic slip on block edges are constrained by horizontal GPS velocities provided by PBO. After assessing all eight models, we conduct a bootstrap analysis on the four best-performing block geometries to obtain histograms and maps of fault slip rates. Results from this analysis suggest that 1) the Little Salmon fault is the major thrust structure in the forearc, 2) the MRFZ is a transpressional structure that accommodates right-lateral shear and 3) the Grogan fault is a predominantly reverse structure. Additionally, our results suggest that seismic hazards in this region are shifted away from the megathrust and onto crustal forearc faults.

Application of High-precision, NLL-SSST-coherence Earthquake Location to Untangle the 3D Seismo-tectonics of the Mendocino Triple-junction, Northern California

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The Mendocino triple-junction (MTJ) hosts complex, 3D plate interactions: dextral Pacific – Gorda plate motion across the Mendocino fault, oblique subduction of the east-dipping Gorda plate under the North American plate along the Cascadia subduction zone and dextral North American – Pacific plate motion across the San Andreas fault. Here we image and interpret the 3D seismo-tectonics of the MTJ using high-precision, NLL-SSST-coherence relocated seismicity from 1982 to 2022. NLL-SSST-coherence relocation (https://doi.org/10.1029/2021JB023190) extends NonLinLoc location to 1) reduce velocity model error through source-specific, station travel-time corrections (SSST) and 2) reduce arrival-time error by merging location information across nearby events defined by waveform similarity, or coherency. This procedure approaches the precision of differential-timing based, relative location methods, while requiring waveforms from only one or a few seismic stations, enabling precise relocation with sparse networks. Robust, composite, first-motion focal mechanisms are generated from ensembles of nearby, similar events.

The relocated MTJ seismicity shows features found in other catalogs, but also differences and new features, especially for the offshore area which lacks station coverage: narrow, deep (~15-20km) and shallow (~5-10km) streaks of seismicity along the Mendocino fault; several ~20-30km deep, NW-SE lineations of events suggesting dextral shearing along fractures within the Gorda plate; diffuse seismicity in the deeper Gorda plate; southward down-warping of the Gorda plate over ~10-20 km north of the Mendocino fault; an apparent, ~5km wide gap in seismicity just north of the Mendocino fault; almost no events within the Pacific Plate; shallow seismicity and larger events (e.g. 1992 Mw 7.2) just north of the Mendocino fault within the North American crust. Relocation with different velocity models shows hypocentral shifts of up to ~7 km, illustrating the difficulty in determining the true depth, shape and dip of the subducting Gorda plate and the absolute geographic location and depth of seismicity in general.

A Linked Sequence of Earthquakes That Initiates at the Northern San Andreas Fault

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A linked sequence of earthquakes started in early 1991 just north of the northernmost San Andreas fault (SAF). Projecting the known trend of the SAF from offshore Point Delgada towards Telegraph Hill on land, as previous researchers have done, points directly to where this linked sequence of earthquakes begins. This northward projection of the SAF trend defines the corner of the Pacific plate, which is also where the Mendocino fault ends: the actual triple junction location.

This linked sequence begins on August 17th, 1991, with the Honeydew earthquake Mw = 6.0, a rare North American plate event (NAP). The next significant event is another NAP event, the 25 April 1992 Cape Mendocino earthquake, Mw= 7.2. This event initiates a response within the Gorda plate below with a pair of damaging events, Mw = 6.5 & 6.6. These aftershocks activate a previously unrecognized NW-SE lineation of events within the Gorda plate, dramatically cutting across the predominant NE-SW fabric documented in this region. The last significant linked event in this sequence is the Sept 1, 1994, Mw = 7.2 quake, which occurs along the central Mendocino fault.

We will describe how each quake leads to the next and propose that this sequence is evidence that the SAF may terminate in shallow reverse structures. This is not a new idea, that somehow the SAF rolls over and is responsible for the uplift of Kings Range. The rupture planes in 1992 and 1991 could be extensions of what is beneath the King Range which supports our hypothesis that the influence of the SAF crosses into the southern Cascadia subduction zone.

Mendocino Triple Junction: Terraces and Tectonics in the Latest and Greatest Quaternary

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The Mendocino triple junction, where the overlapping and interfingering southern Cascadia and northern San Andreas plate boundaries exist, is a complicated tectonic region where oblique convergence and dextral shear interact in interesting ways. Northwest-striking, southwest-vergent thrust faults represent anelastic deformation related to Cascadia convergence and east-stepping Pacific-North America dextral shear generates strike-slip faults that either terminate in uplifted terranes and east-west striking reverse or thrust faults and folds or strike-slip faults that penetrate through and past the Humboldt Bay region.

While the Russ fault is mapped as a north-vergent high angle reverse fault, we locate a topographic scarp adjacent to the Russ fault that suggests a south-vergent reverse fault offsetting late Pleistocene to Holocene fluvial terraces. We conduct a Ground Penetrating Radar survey to explore subsurface evidence for faulting. Using regionally derived incision rates as a proxy for terrace age, we use topographic swath profiles to measure scarp heights and calculate a late Pleistocene slip rate of about 0.75 mm/yr.

We conduct a fluvial terrace mapping campaign to better understand the stratigraphic setting and to provide relative age control for the geomorphic surfaces offset by the fault. This chronostratigraphic framework will form the basis for updated slip-rate calculations made for the scarp-forming fault. We use LiDAR-derived slope rasters to delineate fluvial terrace treads using maximum slopes up to 4°. We calculate the relative elevation for the treads using a relative elevation model that represents the modern floodplain. Using the distribution of relative elevations for each tread we correlate terraces along the lower Eel and lower Van Duzen rivers. Terraces north of the mouth of Van Duzen River display syntectonic deformation in the form of a N20E striking syncline, while there is no apparent folding evident in terrace profiles to the south.

Characteristics, Hazards and Evolution of the Gorda Region of the Cascadia Subduction Zone

Poster Session · Thursday 21 April · Conveners: Jason R. Patton, California Geological Survey (jason.patton@humboldt.edu); Lori A. Dengler, Humboldt State University (lori.dengler@humboldt.edu); Peggy Hellweg, University of California, Berkeley (peggy@seismo.berkeley.edu); Bob McPherson, Humboldt State University (robert.mcpherson@humboldt.edu); Rick I. Wilson, California Geological Survey (rick.wilson@conservation.ca.gov)

Revisiting the M6.5 21 December 1954 Korbel Earthquake

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The December 21, 1954 M6.5 earthquake near Korbel, CA, in Humboldt County remains one of the more interesting North Coast historic events. The felt area extended from north of Coos Bay, OR, to south of Santa Rosa and Sacramento, CA, and eastward past Alturas, CA. Nearby residents considered it the strongest quake since 1906 and fishermen described flow on the Mad River reversing course. It is the only large historic earthquake in the region that may have been located on a surface fault within the overlying North American plate. It was recorded on two nearby accelerometers of the Coast and Geodetic Survey, on stations of the seismographic networks of UC Berkeley and the California Seismological Lab in Pasadena, CA and at regional and teleseismic sites. A variety of investigations between 1954 and the 1980s have produced at least 14 locations clustered between 40.78°N and 124.87°W in the SW and 40.94°N and 124.0°W in the NE. The estimated epicenters are based on analyses of arrival and t_S-t_P times, polarization and/or felt reports. Using data published in various reports and papers, as well as unpublished data from Berkeley's archives, including original recordings, we redetermine the earthquake's hypocenter and evaluate the uncertainties in the estimation. We review the magnitude and estimate a mechanism, in addition to comparing the 1954 event and its aftershocks with event information and data available in the modern catalog and archives.

The December 2021 Cape Mendocino Earthquake Sequence

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California's region north of 40N and west of 122.4W hosts the largest number of the state's large earthquakes and is among its most tectonically complex, with damaging earthquakes on the San Andreas and Mendocino faults, the Gorda and North American plates and on the subduction interface. The active sequence beginning on December 20, at 20:10 UTC with a foreshock/mainshock (FS/MS) pair continues that trend. The FS occurred on the Mendocino Fault at 40.314N, 124.727W, h=15km; the MS followed about 10 s later. For several weeks the FS hypocenter, assigned M_w6.2 based on MS waveforms, represented the two events in catalogs. Based on the improved fit to long-period waveforms in moment tensor analysis, we estimate the MS location as 40.34N 124.3W, h=30 km. The mechanism is strike-slip (99% DC, VR 83%) with fault strikes, dips and rakes of (115, 81, 170) and (207, 80, 9). The FS and MS are quite far apart, with copious aftershocks forming two clusters, one extending along the Mendocino Fault and the other a cloud inland of Cape Mendocino. A variety of analyses suggest that the hypocenter of the MS is onshore. The finite fault best representing the MS lies along a plane (209, 80, 9), with rupture trending to the NE and downward starting at a depth of 15 km and reaching about 20 km. The scalar moment, 1.89e18 Nm, corresponds to M_w6.1. The maximum slip is approximately 1 m. Based on the its depth and the presence of N-S compression, the MS most likely occurred within the Gorda Plate under the North American Plate. We present updated results on the MS, in particular using the GridMT approach to determine the best location and moment of the slip centroid. We also estimate a mechanism and magnitude for the FS and review mechanisms and locations of the aftershocks. We explore finite-source models for the updated MS location and assess the results in terms of the seismicity distribution, onshore deformation, strong ground motion and the local tectonics.

The Humboldt Bay Seismic Network: 1974 to 1986

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The Humboldt Bay Seismic Network (HBSN) became operational in the summer of 1974. Pacific Gas & Electric was requested by the Atomic Energy Commission to evaluate the seismic hazard risks to its nuclear unit on Humboldt Bay.

The station spacing of the HBSN was chosen to facilitate locating events deeper than 15km. Also, using vertical 1hz geophones, single event focal mechanisms were made possible to determine intraplate stress orientations, which became a useful tool. The stations were initially situated around Humboldt Bay, but as time went on, two stations were deployed south of the Mendocino triple junction into the northern San Andreas fault region.

Between June of 1974 to early 1986, over 15,000 earthquakes were located out of more than 25,000 events. Over 1500 focal mechanisms were hand plotted using upper hemisphere projections.

I will present the original figures we used to determine that the offshore Mendocino transform fault was a vertical feature (barrier), and the Gorda plate did not underthrust the Pacific plate anywhere along its extent, as some researchers proposed at the time. The 1975-era cross sections will clearly show the Gorda plate descending beneath western North America at about 11 degrees, with its southern edge defined by the intraplate earthquakes' locations. Slides will be presented on how we divided up the region using focal mechanisms. I will end the presentation comparing what we knew then and what we know now.

The Redwood Coast Tsunami Work Group: Twenty-five Years of Evolving Outreach on California's North Coast

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The Redwood Coast Tsunami Work Group (RCTWG) is an ad-hoc organization formed in response to California's earthquake planning scenario for an earthquake and tsunami on the southern portion of the Cascadia subduction

zone (CDMG Special Publication 115, 1995). It is a volunteer group of local, state, federal agencies, tribes and other organizations where everyone has an equal voice in developing a coordinated approach throughout the three-county region. RCTWG led the State in near-source tsunami messaging and printed materials. In contrast to other parts of Cascadia, RCTWG tailors messaging to the unique Gorda region where felt earthquakes are frequent. The first tsunami hazard maps were released in 2002, updated in 2008 and 2021. In 2008, the RCTWG with the National Weather Service and the California Office of Emergency Services began annual "live code" tsunami communications tests, the only region in the US to do so. For a volunteer group, RCTWG has shown remarkable staying power and participated in a variety of preparedness projects including hazard mapping and sign placement, "Earthquake – Tsunami Room" at County Fairs, public service announcements and print material, assisting in TsunamiReady community recognition, social media campaigns, facilitating numerous multi-agency, multidiscipline coordinated exercises and community evacuation drills. In the COVID era, the RCTWG has focused on electronic media including special web pages featuring personal remembrances of the 2011 Japan tsunami and the appearance of the tsunami boat Kamome at the 2021 Olympic games in Tokyo (rctwg.humboldt.edu). Two fundamental principles underlie RCTWG efforts: all of the information represents best currently available information and may change as we learn more, and we never use fear to promote interest. We emphasize the positive message that actions can reduce risk and provide peace of mind even in the most seismically active part of the lower 48.

The Seismic Saga of the Humboldt Bay Nuclear Power Plant

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In November 2021, PG&E petitioned the Nuclear Regulatory Commission (NRC) to terminate the license for the Humboldt Bay Plant #3, the first commercial nuclear power plant in California. The petition was the official end to a story beginning in the 1950s before global seismic networks, plate tectonics and paleoseismology. The Humboldt Bay site just south of Eureka, California was chosen because of available PG&E property with proximity to water, no known faults and a much less resistant local community compared to proposed sites in Bolinas and Point Arena. The 63 MWe reactor became operational in August 1963 and, for the next 14 years, provided most of the electric power to the Humboldt Bay region. The first local seismic net was established in 1974 when the Atomic Energy Commission (NRC predecessor) became concerned about nuclear plant seismic safety in the wake of the San Fernando earthquake. Teknekron (predecessor of TERA) Corporation established a network of 16 stations, providing the first detailed picture of regional earthquake activity. A scheduled maintenance shutdown in 1976 became permanent when a fault discovered in a nearby quarry led to an investigation of active faulting. Local activists were recognized as official intervenors by the NRC that likely prolonged the shutdown. Woodward-Clyde (now part of URS) began field studies that were still underway when PG&E submitted an application to permanently close the plant and begin the decommissioning process. The March 1979 Three-Mile Island accident had changed the nuclear landscape, and it was not economical to meet the new standards. The story is not completely over; waste still resides on site, now stored in casks just above the modeled tsunami inundation zone. An unintended consequence of Plant #3 is the wealth of geologic data the seismic and tsunami safety studies provided. The former plant site sits only 13 km above the Cascadia interface, a kilometer from the Little Salmon fault, and adjacent to two smaller faults.

Tsunami Hazard Mapping: Comparison of California Mapping with Oregon Mapping

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Tsunami hazards in northern California and southern Oregon pose a significant risk to both residents and visitors to these coastlines. There are notable differences in how tsunami hazards are treated relative to the state border of California and Oregon. Differences appear to be due to both scientific and philosophical reasons and are primarily tied to the perceived change in character and activity of subduction between the Juan de Fuca plate (generally offshore of Oregon) and the Gorda plate (generally offshore of California). We want to better understand these differences and work towards consensus where possible.

Oregon uses their quasi-probabilistic XXL t-shirt sized tsunami model as a basis for the local tsunami hazard areas. This approximately equates to a >5,000-year tsunami event. California uses a probabilistically based 1,000-year (975) tsunami model for their tsunami hazard area. The 1,000-year tsunami model equates to the M sized t-shirt Oregon tsunami model. There are some special locations in California where the 2,500-year (2475) tsunami model is used (e.g., for isolated dune locations). There are also some deterministic sources incorporated into the California hazard area.

We present an overview of these differences.

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: Federica Lanza, Swiss Seismological Service, ETH Zurich (federica.lanza@sed.ethz.ch); Kristine L. Pankow, University of Utah Seismograph Stations (kris.pankow@utah.edu); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Stefan Wiemer, Swiss Seismological Service, ETH Zurich (stefan.wiemer@sed.ethz.ch); Antonio Pio Rinaldi, Swiss Seismological Service, ETH Zurich (antoniopio.rinaldi@sed.ethz.ch); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov)

Managing Induced Seismicity in Near-real Time: A Case History from Finland

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The near-real time effort of managing stimulation induced seismicity discussed here comes from an Engineered Geothermal Systems project located near Helsinki, Finland. The EGS site is on the campus of Aalto University, the aim of the EGS project being to produce a sustainable baseload for the campus-area's district heating network. We show that a combination of episodic stimulation and near-realtime seismic monitoring allowed us to avoid exceeding a regulated maximum MW 2.1 induced earthquake.

A 3.3 km vertical observation well and a deviated 6.4 km measured-depth stimulation well were drilled at the Aalto site in 2017 and 2018, both entirely in crystalline basement rocks. The bottom 1 km of the stimulation well was completed with a 5-stage stimulation assembly. This well was stimulated with a total of 18,160 m3 of water. The stimulation included moving injection intervals and rest periods to control the induced event magnitudes. The stimulation was monitored by a 3-tier seismic network, all telemetered to the project site. Government requirements included a 20-minute reporting time for event size and location. The key element of the monitoring system was a 12-level vertical array of 3-component seismometers placed at 1.9-2.4 km depth in the monitoring well. This array allowed us to detect events down to about magnitude MW -1.5. The proliferation of such small events helped limit potentially project-stopping pumping parameters. This array was complemented by 12 borehole seismometers installed in 0.3- 1.14 km-deep wells and 17 station strong motion network. The 12 stations helped control the lateral positions of events greater than MW ~ -0.5. The near-real time earthquake information was used to controlled pumping rates and well-head pressures. The original stimulation strategy was modified in response to the occurrence of enhanced seismic activity and as understanding of seismic response of the reservoir improved.

Rupture Behaviour of Geothermal Fluid-induced Microseismicity from Combining Directivity and Focal Mechanisms in Helsinki, Finland

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The rupture mechanics of fluid-induced microseismicity (M<2) provide important information about the underlying processes controlling the earthquakes. The governing mechanism at close distances to the well is generally believed to be the pore pressure rather than the local stress field; the rupture directions of smaller events are more random, while the larger events nucleate at the pressure front and propagate back into the pressurized volume towards the well. Consequently, the maximum magnitude (M_{max}) is then defined by the pore pressure front. However, the rupture mechanics of microseismicity can be difficult to study due to the low amplitudes and high frequency content of the signals. In this study, we examine directivity patterns to identify rupture directions and fault planes of the 21 largest earthquakes (M_L 1.3-1.9) recorded during the 2018 St1 Deep Heat geothermal project near Helsinki, Finland, using a surrounding network of 12 geophones.

We apply the empirical Green's function method to isolate the source component of the earthquakes, identifying 11 events with clear variations in corner frequency and source time function pulse width with azimuth. We estimate the associated focal mechanisms using principle component analysis, resulting in oblique reverse faulting as the main mechanism. Assuming a unilateral Haskell rupture, we model the directivity for each event and are able to resolve the rupture direction and fault plane of five events within 100 meters of the well. The rupture directions appear random for all events, supporting that pore pressure is likely controlling the ruptures and showing that combining directivity and focal mechanisms is a useful tool to study the ruptures of small events. Furthermore, we find that the largest event (M_L 1.9) ruptures away from the well. This implies that the largest earthquakes do not necessarily rupture back into the stimulated volume, suggesting less predictability in terms of M_{max} for fluid-induced seismicity.

Seismic Analysis of Reservoir Conditions for Inducing Seismicity at the San Emidio Geothermal Field, Nevada, USA

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At the San Emidio geothermal field, Nevada, a substantial increase in microseismic activity during a power plant shutdown (i.e., cessation of all production and injection activities) was observed in December 2016 by a local seismic network with more than 1,300 vertical component nodal instruments. Here, we present our seismic analysis of the 2016 dataset, including locating microseismic events (MEs), P-wave velocity (Vp) tomography, focal mechanism (FM) inversion and stress inversion, to investigate material properties, distribution of existing faults and local stress state in the reservoir for understanding the mechanisms for inducing MEs during plant shutdown. The Vp model shows large lateral variations, with main structural features that are consistent with normal faults dipping westward. Two low-Vp zones (LVZs) to the west of the surface trace of the main fault and near some operational wells are imaged at depths of ~0.2-1.2 km below land surface. The northern LVZ is closer to two production wells and the southern one is closer to four injection wells. Most MEs occurred within or surrounding the northern LVZ. FM results show diverse faulting regimes, dominated by normal faulting. Stress inversion using high-quality FMs yields a maximum compressive stress axis plunging nearly vertically toward the northeast. The intermediate and minimum compressive stress axes are both nearly close to horizontal toward the WSW and SSE, respectively. Orientations of ME hypocenters and FMs show that a majority of MEs may occur on a large-scale fault and/or some small-scale faults/fractures within the LVZ, suggesting that the activation of faults/fractures due to pore pressure increases caused by the cessation of pumping triggered some of the MEs. Modeling pressure changes due to pumping cessation suggests fluid pressure increases of ~25-50 kPa at the hypocenters of MEs, which are predominantly near shutdown production wells. The work presented herein has been funded in part by the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, under Award Numbers DE-EE0007698 and DE-EE0009032.

Reducing Risk in Geothermal Projects Through Improved Understanding and Characterization of Stimulated Fracture Heterogeneity

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The successful development of geothermal energy from hydraulic fractures and stimulated natural fractures (EGS) has been an elusive goal for over forty years. In many cases, the temperatures of production water have declined earlier than expected an effect often attributed to "short-circuiting". A review of the analytical solutions of for EGS shows that the time to thermal breakthrough has second power dependencies on the heat-exchange surface area and the circulation rate. Numerical experiments show that heterogeneity of the transmissivity significantly reduces the effective heat exchange area. Designing EGS systems based on assumptions of homogeneity can result in erroneous predictions of thermal performance.

A key to reducing risk in EGS development is predicting the effective heat exchange area. Underground experiments, such as EGS COLLAB, are important for developing EGS characterization strategies that address the critical design parameters. EGS COLLAB consists of multiple experiments with heat and tracer circulation in induced and stimulated fractures on 10-m scales. The experiment borehole arrays were drilled from mine openings between 1250 and 1500 m depth in the metamorphic rock of the Sanford Underground Research Laboratory, South Dakota (former Homestake Mine). The arrays surround the stimulated volume of rock. The two test blocks are well-characterized using seismic tomography, electrical resistance tomography and extended hydrologic characterization including tracer tests. Passive seismic monitoring, continuous active source seismic monitoring (CASSM), dynamic ERT imaging using high contrast fluids, acoustic emissions and distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), strain (DSS) changes and tracer tests were used to monitor flow and stimulation tests and fracture aperture strain monitoring was performed using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool. The open-access results of the experiment are providing a sound basis for understanding stimulated fracture network geometry.

Statistical Bounds on How Induced Seismicity Stops

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Earthquakes caused by human activities receive scrutiny due to the risks and hazards they pose. Seismicity that occurs after the causative anthropogenic operation stops has been particularly problematic—both because of high-profile cases of damage caused by this trailing seismicity and due to the loss of control for risk management. With this motivation, we undertake a statistical examination of how induced seismicity stops. We borrow the concept of Båth's law from tectonic aftershock sequences. Båth's law anticipates the difference between magnitudes in two subsets of seismicity as dependent on their population count ratio. We test this concept for its applicability to induced seismicity, including ~80 cases of earthquakes caused by hydraulic fracturing, enhanced geothermal systems, and other fluid-injections with clear operational end points. We find that induced seismicity obeys Båth's law: both in terms of the magnitude-count-ratio relationship and the power law distribution of residuals. Furthermore, the distribution of count ratios is skewed and heavy-tailed, with most earthquakes occur during stimulation/injection. We discuss potential models to improve the characterization of these count ratios and propose a Seismogenic Fault Injection Test to measure their parameters *in situ*. We conclude that Båth's law quantifies the occurrence of earthquake magnitudes trailing anthropogenic operations.

Local Seismic Monitoring of a Stimulation at the Utah Frontier Observatory for Research in Geothermal Energy Site

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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site is a Department of Energy funded research facility whose mission is to promote the development of technologies needed for enhanced geothermal energy production. Research topics are related to drilling, reservoir development, fluid exchange and methodologies to mitigate induced seismicity. At the Utah FORGE site, seismic monitoring consists of two phases: (1) monitoring reservoir development (presented in the companion abstract, by Dyer et. al) and (2) local monitoring of induced seismicity. In February 2021, the first horizontal well was completed and the plan is for this well to be stimulated in mid-March 2022. The local 14 station seismic network includes a combination of shallow borehole broadband and strong-motion stations, surface broadband stations and strong-motion stations near structures. The seismic data from this network are integrated into the regional monitoring at the University of Utah Seismograph Stations. Automatic alarms are configured to alert based on a Traffic Light System developed for Utah FORGE. We present details on the local seismic network, background seismicity, the Traffic Light System and preliminary results from the March well stimulation, including any alerts.

Seismic Monitoring Around a Potential Deep Geothermal Site in Upstate New York: CorNET

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As part of a plan to achieve carbon neutrality by 2035, the Cornell University Ithaca NY campus is exploring the capability of deep geothermal earth source heat to provide campus-wide heating. The campus environment, on 3 km of flat-laying Paleozoic sediments over basement, typifies continental interiors worldwide, so lessons learned here should provide insight into the potential for geothermal heating in many places. In advance of potential production, a pilot borehole observatory is being drilled to basement depths in 2022 and a microseismic network has been deployed to constrain background seismicity since mid-2019. The microseismic network termed CorNET, operated by ARA for Cornell, consists of 15 short-period telemetered stations, seven in boreholes, in the greater Ithaca NY area. It has been operating with all data openly available, in an effort to maximize transparency of this high-visibility project. Initial earthquake locations are now being routinely produced. Nearly all detected events are either outside the array or cultural in origin, many due to local construction. Nevertheless, several detectable and locatable earthquakes have been identified, mostly a few tens of km outside the network and/or of magnitudes less than 1.0. Since CorNET was deployed the regional catalogs do not show any events within 100 km of Ithaca, indicating the need for local monitoring to quantify seismicity rates. Assessing this low rate of seismicity will be critical to establishing a baseline as drilling and potential geothermal resource work continues. These data also provide signals useful for characterizing structure, complementing previous site characterization studies around the drill site.

The DEEP Project: Establishing a Full-scale Real-time Test Bench for Seismic Monitoring and Forecasting at the Utah FORGE EGS Site

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Many countries worldwide are investigating the potential of deep geothermal energy as they plan to address future energy needs with more renewable solutions. In order to facilitate this transition, it is critical to gain more experience with the technologies of Enhanced Geothermal Systems (EGS) and to demonstrate that safe and sustainable development of deep geothermal energy projects is possible. In particular, to develop EGS, induced seismicity, which is not an undesired by-product but a necessary tool to create a productive heat exchanger, needs to be adequately managed and controlled. The DEEP (Innovation for De-risking Enhanced geothermal Energy Projects) project is an international collaborative research environment whose goal is to establish a full-scale real-time test bench for innovative seismic monitoring and processing, seismicity forecast modelling and risk assessment using the so-called Adaptive Traffic Light System (ATLS), a fully probabilistic seismic hazard and risk study that is updated continuously as new data arrive. Field test sites in DEEP include the Frontier Observatory for Research in Geothermal Energy (FORGE) in Utah (USA), as well as EGS sites in Germany and France. Key to the project is also the definition of next-generation good-practice guidelines and risk assessment procedures in order to reduce commercial costs and enhance safety of future projects. Here, we will present an overview of the DEEP project to provide a framework for other DEEP presentations. We will also showcase a selection of results from new event detection and location algorithms using machine learning and Distributed Acoustic Sensing (DAS), together with the first forecast models performed both on synthetic and real data from the first FORGE stimulation.

Induced Micro-seismicity Monitoring in Urban Context Using Seismic Arrays

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Induced micro-seismicity monitoring is generally performed using seismic surface networks, which can be limited by a significant ambient surface noise level in particular in urban contexts. To reduce the impact of this noise, an alternative to borehole stations consists in operating with dense surface seismic arrays. Here we investigate the Strasbourg induced earthquake sequence, occurring since mid-2018 around the Geoven deep geothermal doublet operated by Fonroche in Vendenheim (France). So far, the BCSF-Rénass (French national observatory) has recorded 576 induced earthquakes using classical surface seismic networks. Their catalog is complete down to magnitudes 0.6, containing events with a magnitude up to 3.9, including 22 with Mlv>2 and 4 with Mlv>3. These events are organized into two distinct swarms: a first swarm in the vicinity of the Geoven wells and a second one 4-5km South from it. Although the project has been forced to stop because of the felt and damaging induced seismicity, the Northern swarm is still active. To improve our knowledge of this seismic crisis, we deployed seismic arrays of SmartSolo nodes around the active swarm, recording for several months starting after the two biggest recent events. The aperture of each array is around 70m, providing a high-resolution acquisition for these local seismic events. As the arrays are located right above the seismic events hypocenters, the front waves illuminate the arrays with a significantly higher apparent velocity than surface waves. We use a beamforming technique to characterize the local ambient noise and waveform stacking techniques to increase significantly the SNR, in particular with phase-weighted stacking. This allows us to detect events down to magnitude -0.5 and 4 times more events than the BCSF-Rénass catalog. We use Matched-Field Processing to locate these events and compare them with location performances of traditional networks.

The Importance of Induced Seismicity Monitoring to De-risk Geothermal EGS Projects

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The world needs Terawatts of 24/7 clean renewable electricity. Geothermal energy has a high potential to become a significant power source to meet this need. The Earth's heat is accessible anywhere. Geothermal energy can provide electricity that is cost-competitive with natural gas, coal, wind and solar and fracturing techniques from the oil and gas (O&G) industry can be applied to harvest heat from hot dry rock. Fracturing creates an artificial reservoir in hot dry rock in which fluid can be circulated to harvest heat. However, there are concerns with induced seismicity with fracturing and in recent years geothermal projects in igneous rock have reported seismic events, likely associated to the geothermal project activity.

For that reason, Sage Geosystems considers it critical to monitor, analyze and report potential induced seismicity in the vicinity of their geothermal well test in the JFB Heard Estate 1 well in Starr County, Texas. Sage and the Bureau of Economic Geology deployed a seismic array of four stations in the vicinity of the well prior to any operations. Our goal is to record background seismicity prior to operations that include fracturing operations in sedimentary rock to connect two clusters of lateral boreholes separated by 350 ft at an approximate depth of 11,000 ft.

Sage will drill a cluster of eight 1-inch laterals extending 300 ft from the wellbore at a depth of 11,230 ft and another cluster of eight 1-inch laterals at

10,880 ft. They will then perform a series of fracture treatment operations to connect these two clusters, allowing fluid circulation in the rock to harvest heat.

Induced seismicity monitoring and assessment will continue throughout the operations and during subsequent circulation operations to identify possible earthquake risks and mitigation. De-risking includes high resolution earthquake catalogs and a seismicity response plan in case seismic activity is detected at the vicinity of the well.

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances

Poster Session · Wednesday 20 April ·Conveners: Federica Lanza, Swiss Seismological Service, ETH Zurich (federica.lanza@sed.ethz.ch); Kristine L. Pankow, University of Utah Seismograph Stations (kris.pankow@utah.edu); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Stefan Wiemer, Swiss Seismological Service, ETH Zurich (stefan.wiemer@sed.ethz.ch); Antonio Pio Rinaldi, Swiss Seismological Service, ETH Zurich (antoniopio.rinaldi@sed.ethz.ch); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov)

Ambient Noise-based Monitoring of Seismic Wave Velocity Modulations at the Carbfix Reinjection Site, SW-Iceland

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In an effort to tackle the climate crisis, since 2014, CO_2 and H_2S emissions from the Hellisheiði Geothermal Power Plant at Iceland are injected and stored underground as part of the CarbFix project. The CarbFix project has proven to be efficient in reducing emissions of CO_2 and H_2S by turning these gases into stable minerals through reactions with basaltic subsurface rocks. In this study, we monitor changes in the subsurface structure down to the geothermal reservoir utilizing the ~2-year-long continuous recordings, starting from Oct 2018, of six seismic stations deployed near the Hellisheiði power plant. We compute the auto- (ACF) and cross-correlation functions (ANC). For the ACF, we observe a strong seasonal variation in the dominant spectral peak (f_0), which oscillates around ~0.2 Hz. Interestingly, we found secondary spectral peaks (f_1 and f_2) at exactly 3 and 5 times the dominant frequency. We interpret these peak frequencies, at $f_n = (n+0.5)/t_r$, as reflected P waves that have a negative polarity and two-way travel time of t_r = ~2.5 s. The reflected P wave and its multiples are clearly observed in ACFs filtered between 0.4-2 Hz. The relative travel time changes (dt/t) of the reflected P wave show a complex pattern with both short-term (a few days) and long-term (monthly to annual) variations. These variations are likely the result of fluctuations in both velocity structures and the depth of the reflection interface due to the power plant operations. For the ANC, we monitor the subsurface velocity structure using coda waves. Besides, we also demonstrate that robust temporal pattern of velocity changes can be estimated using surface waves extracted from ANCs computed for a triplet of stations that are almost aligned in a straight-line. All the resulting temporal changes of seismic velocities will be presented and modeled to infer the dominating mechanism by incorporating injection, production and environmental data in our presentation.

Building a Probabilistic Seismic Hazard and Risk Model for EGS Stimulations

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Most traffic-light systems (TLS) related to Enhanced Geothermal Systems (EGS) and hydraulic fracturing (HF) stimulations adopt oversimplified metrics (e.g., the maximum observed magnitude) to aid decision making by stakeholders. Recently attempts have been made to incorporate more efficacious metrics such as nuisance risk or damage potential. Ideally, the next-generation of TLS will be both adaptive and risk-based. To that end, as part of the monitoring of the 2022 EGS stimulation at the FORGE site in Utah, we built a site-specific probabilistic a-priori seismic hazard and risk model, in order to assess the potential effects of the upcoming stimulation around the site. The calculations were done on OpenQuake and the complete logic tree had dozens of branches, with different branching levels for the seismicity rate model, the b-value, the maximum magnitude and the ground shaking intensity model. The results include hazard curves (pseudo-spectral acceleration at 0.3 seconds at 5 km distance), Modified Mercalli Intensity maps around the site and fatality risk for individuals in a hypothetical timber house 5 km away from the injection well. Here we discuss the sensitivity of the results to certain decisions made during the construction of the logic tree, as well as adaptive schemes that can be used in future refinement of the logic tree weights in light of new observations.

Compact Broadband Instrumentation for Geothermal Field Monitoring

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Geothermal energy is a rapidly growing area of interest as we look towards renewable sources of energy. Broadband seismometers are an increasingly important tool being utilized in all stages of the geothermal energy lifecycle, from the initial exploration phase through to production. The risk of induced seismicity as a result of pumping high pressure fluids must be effectively monitored to ensure safe operation.

Operators are making use of a mix of both sub-surface and surface stations to effectively monitor geothermal well operation. When monitoring stations make use of broadband instrumentation, the stations can be sparser in their distribution which is often more cost effective compared to large arrays of geophones. Broadband seismometers can record lower frequencies between 1s and 120s, providing more accurate moment magnitude (MM) estimates than geophones at larger magnitudes (MM 1-2), which is important to maintain the integrity of any traffic light monitoring regulations that may be in place.

Guralp Systems have developed a range of smart seismic sensors and data acquisition technologies that aid operators when instrumenting geothermal fields. The Certimus is a compact broadband seismometer which incorporates digital feedback sensor technology with the Minimus digitizer allowing for easy configuration. The digital feedback system means that the sensor can be easily deployed by operators and will work at any angle, allowing the instrument to be deployed with confidence. This same omnidirectional, easily configurable sensor platform is also designed into other packages suitable for sub-surface deployment, suiting all aspects of the geothermal monitoring system. Guralp have had over 15 years of experience of supplying broadband instrumentation for monitoring geothermal fields and has worked with a number of partners to provide turnkey solutions.

Insights Into Hydraulic Fracturing Processes From Waveform-similarity Analyses of Acoustic Emissions Induced in Mine-scale Experiments

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Implementing efficient and safe enhanced geothermal systems requires a profound knowledge of fracture processes. However, linking laboratory and field-scale observations remains challenging. In-situ mine scale experiments can further reduce the gap between the two scales. We present results of an event cluster analysis based on network-based waveform-similarities from in-situ hydraulic fracturing experiments conducted in crystalline rock at the Äspö Hard Rock Laboratory (Sweden). The injection experiments induced ~20,000 acoustic emissions (AEs) in the vicinity of hydraulic fractures with lengths of a few meters. The inversion for focal mechanisms (FM) for these AEs is limited to the largest events and suffers from increased uncertainties due to limited knowledge of the sensor characteristics and the coupling of the sensors to the rock. Relative waveform analyses, such as our approach, help overcome these limitations. We can increase the number of events with qualitative mechanism estimates by combing the clustering results and FM solutions. Besides, the subtle changes in the recorded waveforms allow following the fracture evolution in greater detail compared to spatial analyses based on the AE catalog alone, even without having information about the FMs of these events. We find clear differences between the experiments, which we discuss regarding changes in injection schemes or local rock properties.

Similar Event Clusters and Microseismic Event Relocation at the Utah Forge Site

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Monitoring and characterizing the microseismicity is crucial in applications of Enhanced Geothermal Systems (EGS). Accurate location estimates of microseismic events can illuminate the fracture openings that will provide the means of geothermal energy production. Here we present preliminary results for microseismic event analyses at the Utah FORGE (Frontier Observatory for Research in Geothermal Energy) site. We use the existing microseismic event catalog from Phase 2C, which includes 424 events ranging from magnitude -2 to -0.5 from April 21, 2019 to May 2, 2019. We use the events recorded on borehole geophones, borehole encased iDAS cable and surface nodal array. We integrate the data from the three different receiver sets and compare their capabilities for microseismic monitoring. We further calculate waveform cross-correlation between all event pairs and determine similar event clusters. We will apply a double-pair double difference method by taking both the differential time between event pairs on same station and between station pairs for the same event to develop a high resolution microseismic event catalog. The high-resolution catalog will be used to interpret the main structures as illuminated by the microseismicity. These results are part of an ongoing project aimed at estimating the state of stress in the reservoir. Next steps involve determining the focal mechanism solutions and constraining the slip directions on the structures. Updated results will be presented at the meeting.

Using Machine Learning for Characterizing Induced Microseismics at the Forge Geothermal Site

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Recent developments in applying machine learning (ML) for earthquake detection and phase picking have demonstrated its superiority over traditional automated earthquake detectors and phase pickers in both efficiency and precision. In classical event location workflows phase association is required to link the picked phases to certain seismic events, which is particularly challenging for events with short inter-event times and/or overlapping phases. This is ever more so true in enhanced geothermal systems (EGS), where many micro-earthquakes are intentionally created to increase the rock permeability in a relatively short time (in terms of hours). The induced microseismic events are often characterized by short inter-event times and overlapping phases challenging the classical event detection and location workflows. To address this issue, we developed a new workflow integrating ML and waveform migration techniques for automated event detection and location. The new workflow does not require phase picking and association and thus is particularly suitable for processing microseismic events in EGS environments.

We applied the proposed workflow to the FORGE seismic monitoring dataset collected at the FORGE geothermal laboratory site in Utah, where stimulation is performed to create pathways for hydrothermal circulation. Continuous microseismic data are acquired in borehole geophone chains located in multiple monitoring wells surrounding the injection well. To evaluate the ML performance to detect and pick induced microseismic events, we first compare various ML models. The best model is therefore chosen as the phase probability generator in the new proposed workflow. Continuous phase probabilities generated by the ML model are then back-projected and stacked to locate the induced microseismic events. Finally, we further evaluate the real-time monitoring feasibility of the new proposed workflow.

Using the 2009 Basel Enhanced Geothermal Systems Project as a Proxy for Predicting Reservoir Development at Utah Forge

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Enhanced geothermal systems (EGS) are created by injecting water into hot, dry subsurface rocks at high pressures in order to form a reservoir. They have the potential to improve the accessibility of geothermal development and accelerate production in the renewable energy industry. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a Department of Energy funded research facility to develop the requisite technologies needed for EGS production. The first deviated well at Utah FORGE was completed in February 2021 and the next stage of the project is stimulating the toe of this well, which is scheduled for the spring of 2022. In this study, we use seismic data collected from the 2009 Basel, Switzerland, EGS stimulation as a proxy for what we might expect during the Utah FORGE stimulation. Basel, like FORGE, experiences low levels of background seismicity and has granite as its reservoir source rock. We analyze the Basel seismic sequence by deconstructing the injection into intervals of 400 cubic meters of injected fluid, documenting the spatial growth of the reservoir boundary, determining the total number of events per injection interval, and determining the moment of the largest event detected per injection interval. We compare the results from Basel with data from a matched filter enhanced catalog of a small-scale stimulation in a test-well at FORGE in 2019. Using these results, we project what we may observe for the 2022 stimulation.

Development, Enhancement and Validation of Seismic Velocity Models

Oral Session · Thursday 21 April · 4:30 PM Pacific

Conveners: Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); Evan T. Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Andreas Plesch, Harvard University (andreas_plesch@harvard.edu); William J. Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Seismic Velocity – Depth Relations for San Francisco Bay Area Sediments and Effects on Simulated Ground Motion in the East Bay

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We obtain new seismic velocity-versus-depth relations for San Francisco Bay, CA sediments from local borehole data and implement them into the USGS San Francisco Bay Region 3D seismic velocity model (SFVM; Aagaard and Hirakawa, 2021). The updates allow ground motion simulations to better reproduce earthquake ground motions in Quaternary sediments. In this region, moderate (Mw ~3.5-4.5) earthquakes generate long-duration, high-amplitude coda waves but these are not reproduced in simulations using the current SFVM (e.g., Aagaard et al., 2010; Hirakawa and Aagaard, 2022, in revision). We believe the shallow seismic velocities in the SFVM are not low enough to trap seismic energy in the ~100-200 m layer of Quaternary sediments underlying much of the area. This effect is most significant in the very low velocity (Vs<200 m/s) Bay Mud. To better account for the properties of these sediments, we fit power-law velocity-depth functions to data points derived from 1D velocity data from local boreholes (Boore, 2003). These velocity profiles are associated with geologic logs that describe sediment texture of each layer, allowing subsets of the velocity-depth data to be fit separately based on grain size (for example, fine, medium, coarse). To apply these new relations, we separate the Quaternary zone of the SFVM into surface units mapped by Witter et al. (2006) and choose the appropriate velocity-depth function to apply to each unit based on their textural description. We use SW4 (Petersson and Sjogreen, 2017), a finite-difference seismic wave propagation code, to simulate motions from moderate magnitude earthquakes with hypocenters in the East Bay and find that the new model allows significantly more seismic energy to be trapped in the Quaternary zone, improving fits to data. Overall, the updates improve synthetic cumulative absolute displacement and peak ground velocity relative to observations, specifically in Bay Mud, which underlies a significant amount of urban infrastructure.

Validation of the Southern California Earthquake Center (SCEC) Community Velocity Model (CVM) Version S4.26-M01 Using 0-5 Hz Deterministic 3D Ground Motion Simulations for the 2014 La Habra, California, Earthquake

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We have simulated 0-5 Hz deterministic wave propagation for a suite of 17 models with the 2014 Mw 5.1 La Habra, CA, earthquake in a 148 km by 140 km area of the SCEC CVM Version S4.26-M01 using a finite-fault source, with validation against strong motion data at 259 sites. Our simulations quantify the effects of statistical distributions of small-scale crustal heterogeneities (SSHs), frequency-dependent attenuation Q(f), surface topography and near-surface low velocity material on the resulting ground motion synthetics. The shear wave quality factor Qs(f) is parameterized as Qs,o (less than 1 Hz) and Qs,o f^{gamma} (f larger than 1 Hz). We find the most favorable fit to data for models using ratios of Qs,o to shear-wave velocity Vs of 0.075-0.1 and gamma values of 0.0-0.4. We apply a generic overlay based on Vs30 that tapers the upper part of the model to merge with the tomography-constrained part of the model, primarily to alleviate unrealistically large near-surface Vs values at rock sites in the CVM. Here, our simulations provide the best fit by extending the Vs30-based taper of the shallow velocities to about 1000 meters. Models including topography and a realistic near-surface weathering layer tend to increase peak ground velocities (PGVs) at mountain peaks and ridges, with a corresponding decrease behind the peaks and ridges in the direction of wave propagation. We find a clear negative correlation between the effects on PGV amplification and duration lengthening, suggesting that topography redistributes seismic energy from the large-amplitude first arrivals to the adjacent coda waves. Our models including topography tend to improve the fit to data, as compared to models with a flat free surface. Our results demonstrate that it is feasible to use fully deterministic physics-based simulations to estimate ground motions for seismic hazard analysis up to 5 Hz, including the effects of, and trade-offs with, near-surface low-velocity material, topography, SSHs and Q(f).

Inverting for Velocity Profiles in California Using Low- and High-frequency Rayleigh-wave Dispersion With Horizontal-to-vertical Spectral Ratios

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Subsurface velocity and density structure play a critical role in earthquake ground motions. Indirect methods such as Multi-channel Analysis of Surface Waves or body-wave travel-time tomography typically use a single set of observations (i.e., Rayleigh-wave dispersion measured over a limited range of frequencies in the former and P- or S-wave travel times in the latter), which can lead to significant uncertainty in the resulting subsurface velocity model and in subsequent estimates of earthquake ground motions. We explore this problem by inverting for a greater diversity of observations—including low- and high-frequency Rayleigh-wave dispersion and earthquake horizontal-to-vertical spectral ratios (EHVSRs)—at selected stations throughout central and southern California. These inverted profiles are compared to the Southern California Earthquake Center community velocity models, cvms4.26 and cvmh15.10, with the application of the Ely geotechnical layer, the USGS Bay Area velocity model, and the USGS National Crustal Model for seismic hazard studies. Dispersion and EHVSR observations are compared to predictions from these models, and modifications to the USGS National Crustal Model—needed to better fit observations—are investigated.

Not surprisingly, significant differences between models are present, which reflect the different datasets used to constrain them. Some are based on an underlying geologic model with rules defining the depth dependence of velocity and density for different rock types. Others rely on tomographic inversion. In all cases, these models tend to average over fine-scale lateral heterogeneity. At the same time, our site-specific inversions assume 1D structure and neglect 3D effects, and both problems can obscure comparisons between our inversions and existing 3D models.

A Large-scale Application of Multizonal Transdimensional Bayesian Inversion for Developing a 3D Geophysical Model in Basel, Switzerland

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Local shear-wave velocity (Vs) structure and sedimentary thickness are considered to be the controlling parameters in seismic amplification. Using dispersion characteristics of surface waves from ambient vibration array data has proven to be an effective tool for imaging subsurface Vs profiles. However, the conventional optimization inversion techniques are limited in their ability to account for the inherent non-uniqueness of this inverse problem and related uncertainty of the profiles. Therefore, we apply a novel Bayesian inversion approach based on a Multizonal Transdimensional Inversion (MTI) with the aim of developing a 3D Vs model for Basel, Switzerland. It is based on a joint inversion of multimodal Rayleigh- and Love-wave dispersion curves (DCs) along with Rayleigh-wave ellipticity. The key advantages of the MTI are that the number of layers is determined self-adaptively from the measured data and model uncertainties can be assessed quantitatively. Moreover, the solution of the Bayesian inversion is the posterior Probability Density Function that results from prior expectations and observed data supplemented by an expected distribution of data errors. Hence, the model uncertainty can be duly propagated from DCs to Vs profiles.

We apply MTI to retrieve 1D Vs profiles from 32 passive arrays located within about 130 sq. km area by using single-zone transdimensional model space with homogeneous prior assumptions. It delivered a major improvement in our results because such joint inversions of surface wave dispersion and ellipticity curves could be performed only for a few sites in Basel in the past. Mulitizonal inversion is performed by drawing additional constraints on depths of intermediate layers from a rigorous 3D geological model. The results are promising in better resolving the interfaces corresponding to major velocity contrasts and the rate of Vs change with depth, especially in the complex sedimentary structure of the Rhine Graben formation.

Three-dimensional Seismic Response of Maar Volcanic Structures

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A maar is a low-relief volcanic crater caused by a phreatomagmatic eruption, usually filled with a mixture of loose fragments of volcanic rocks. Recently, we performed seismic noise measurements at number of such maar structures and identified very characteristic seismic response. Both horizontal and vertical ground motions are extremely amplified with respect to outcropping bedrock (amplification factors up to 100). In order to explain these observations, we have developed simplified 3D seismic velocity models and simulated their response. The models of consist of seismic velocities, density and quality factors capturing the attenuation. The seismic wave field is simulated with finite difference method using random distribution of the seismic sources. The seismic noise is synthetized for seismic stations inside and outside of the maar's infills. Using site-to-reference spectral ratios we determine the amplification and resonance frequency of the infills. The maar infills are modelled as circular or elliptical cones with different ratios between lateral and vertical dimensions in order to study seismic noise amplification resonance frequency and amplitude. We show the uncertainty regarding the depth resolution of the models and additionally the ground motion amplification related to these models. These results are then compared with observed values and the properties of the model are changed in an iterative scheme until we obtain the best fit.

Development, Enhancement and Validation of Seismic Velocity Models

Poster Session · Thursday 21 April · Conveners: Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); Evan T. Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Andreas Plesch, Harvard University (andreas_plesch@harvard.edu); William J. Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

3D P- and S-wave Active-Source Seismic Tomography of Rock Valley, the Nevada National Security Site

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The Rock Valley Fault Zone (RVFZ) is a ~4 km-wide group of active, left-lateral strike slip faults that trend northeast within Rock Valley (RV), in the southern Nevada National Security Site. The RVFZ has hosted a number of magnitude > 3 events, and in May 1993, a shallow (< 3 km) magnitude 3.7 event occurred at the RVFZ and triggered over 600 aftershocks in the five months following. Precise hypocentral locations require a local seismic study in order to refine seismic velocities and constrain the faults at depth. We conducted an active-source accelerated weight drop (AWD) experiment over the central RVFZ area in April and May of 2021. We deployed 188 3-component seismometers along several intersecting transects at ~100 m spacing and recorded 553 AWD vertical and side hits. The waveform data were processed into shot gathers from which we picked P- and S-wave travel-times. We then inverted these picked travel-times for 3D P-wave velocity (Vp) and S-wave velocity (Vs) structure using a linearized, iterative, least squares inversion scheme. We resolved velocities as deep as 600 m, with Vp and Vs structure consistent with the local geology of the RVFZ. We imaged lower velocities at depth to the northwest in a volcanic domain and higher velocities to the southeast in a carbonate domain, with Vp reaching 3 km/s at ~200 m below the surface to the northwest and ~150 m below the surface to the southeast. Just to the north of, and bounded by, the central fault strands is a lower velocity region that is ~ 1 km wide and persists to the deepest part of the velocity model. Vp in this region reaches 3 km/s at ~300 m below the surface. The lower velocity region could be caused by enhanced faulting and fracturing. These local 3D Vp and Vs models will be incorporated into regional models to be used for more precise earthquake hypocentral locations.

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3D Wave Propagation Simulations of m6.5+ Earthquakes on the Tacoma Fault Considering the Effects of Topography, a Geotechnical Layer and a Near-fault Damage Zone

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The U.S. Geological Survey's 3-D Cascadia Seismic Velocity Model (CVM) is commonly used to describe Earth structure when simulating earthquakes in western Washington, Oregon and Northern California. By considering results from seismic tomography surveys and regional geologic mapping, the CVM reasonably constrains seismic velocity throughout the region. However, the model does not include a geotechnical layer and has only rudimentary shallow (<100 m depth) velocity information. In preparation for high frequency (>1 Hz), direct earthquake simulations, we make targeted updates to the CVM to account for greater near-surface and near-fault complexity. These updates include adding surface topography, a shallow, low-velocity (~100 m/s) geotechnical layer, and near-fault damage zones. The updates are made in addition to imposing a frequency-independent attenuation model and small-scale, S-wave velocity heterogeneity throughout the shallow crust. We investigate the impact of these changes by simulating a suite of M6.5+, kinematic rupture scenarios on the Tacoma Fault, a crustal reverse fault in Washington State's Puget Sound region. Simulations are run in 3-D using a spectral element method code (SPECFEM3D) on a mesh with a finely sampled topographic surface. The resulting ground motions can be resolved up to 3 Hz. We compare simulated ground motions between the different iterations of the CVM to one another and validate them against the empirically predicted peak ground motions from the 2014 NGA-West2 ground motion models. The results from this work provide a framework for updated seismic hazard analysis and direct earthquake simulation in the Pacific Northwest.

A High-resolution Phase Velocity Inversion for Crustal Structure of the Southeastern US Using Non-linear Signal Comparison

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Determining the structural relationship between the Suwannee and its adjacent terranes on the margin of Laurentia is critical to understanding the formation of Laurentia and the tectonics of the Alleghenian orogeny. Previous studies demonstrated that the formation of the passive continental margin resulted from the movement of Laurentia towards the west-northwest during Proterozoic rifting. In our study there are two primary goals: 1) create high-resolution velocity maps to accurately quantify the extent of the terrane boundaries, 2) estimate the potential of the Non-linear Signal Comparison method in improving the phase velocity estimates using ambient noise data.

We use vertical-component ambient noise data from 100 broadband seismic stations (EarthScope FlexArray project called SESAME (Z9 2010-14; Parker, 2015)). Several approximately linear array subsets are used to obtain Green's function. Then the phase velocities between two stations are estimated using Non-Linear Signal Comparison (NLSC; Zheng and Hu, 2017). This method mitigates the non-uniqueness problem at deeper depths. Phase velocities are estimated for Rayleigh waves at periods (15-45s) to obtain phase velocity dispersion curves. These dispersion curves are inverted to obtain 1D shear wave velocity profiles at locations along a transect; these profiles are then interpolated to produce 2D models.

NLSC improves the accuracy of Green's functions, particularly at longer periods, by reducing the uncertainties of phase velocity estimates in dispersion curves at lower frequencies. Here, the time lag between two Green's functions is not used directly. Instead, the exponent of the time lag is used and the normalized dispersion spectrum is calculated to estimate the dispersion curve. Dispersion curves are used to model the shear wave velocity using a Bayesian approach (Markov Chain Monte Carlo), which provides the maximum likelihood estimate of shear wave velocity. Results using real data show significant improvement in the estimation of Rayleigh wave phase velocity, particularly in the lower crust and uppermost mantle, compared to conventional techniques.

Calibration, Validation and Application of a Seismic Velocity Model for Coastal South America Using 3D Deterministic Numerical Simulations

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Given the high seismic activity and risk of earthquake damage in the Peru-Chile coastal regions along the South American subduction zone, it is crucial to properly estimate the level of ground motions expected for future ~M9 megathrust events, where acquiring a reliable seismic velocity model is one of the most important steps. In this study, we have applied deterministic wave propagation simulations in central and southern Chile, to calibrate and validate a 3D Community Velocity Model (CVM) for this region. The CVM is based on the background models LITHO 1.0 crust and lithospheric model by Pasyanos et al. (2014) and Lawrence Livermore National Lab Global 3D seismic tomography model (Simmons et al., 2019) down to the depth of 160 km. In addition, we have incorporated more detailed features into the model, including the SLAB 2.0 subduction zone geometry model (Hayes et al., 2018), ambient noise tomography across Central Andes (Ward et al., 2013) and the Santiago de Chile basin model with a modified sediment-bedrock interface (Pilz et al., 2011). Finally, we have incorporated 1D borehole data from the Concepcion and Vina del Mar areas into the CVM and introduced bathymetry data from GEBCO-2019 and a geotechnical layer following Ely et al. (2010).

We have validated the CVM using deterministic wave propagation simulations of the 2010 Mw8.8 Maule, Chile, earthquake, carried out with the discontinuous mesh finite difference code AWP-ODC up to 4.5 Hz. Our source model consists of a smooth background slip distribution with superimposed high stress-drop subevents (Frankel, 2017), with optimization of the location of the subevents using strong motion data, which provided satisfactory fit of the synthetics to strong motion data and ground motion prediction equations. Furthermore, we will present scenario simulations for future extreme megathrust events, to provide risk assessment for densely-populated urban areas using the validated CVM.

Deep Crustal P and S Wave Velocity Models for Oklahoma Based on Common-mid-point Sorting and Stacking of Local Earthquake Waveforms

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The decade long record of induced seismicity in Oklahoma serves as an unintended large-scale seismic experiment. The source-receiver geometry of the local earthquakes and seismic networks allows investigation of the mid to lower crust through long-offset recordings of Pg and Sg phases. However, the irregular and sparse receiver geometry and low signal-to-noise (S/N) ratio at large offsets challenge phase correlation and tomographic methods based on individual travel time picking. To increase the S/N ratio for larger offsets, we employed an alternative processing technique based on common-mid-point sorting and stacking of Pg and Sg phases. Stacking of waveforms reduces the influence of earthquake hypocenter and origin time errors and results in low-resolution, large-coverage, robust and deep crustal 3D seismic velocity models. Pre-processing of the data involves band-pass filtering, conversion to envelope and STA/LTA detection that conditions the data for stacking and increases the S/N ratio. We further perform common-mid-point sorting, stacking and inversion of Pg and Sg phases and obtain localized 1-D velocity-depth functions which were eventually combined into 3D velocity models. We used local earthquake waveforms from 27,582 events recorded between January 2010 and September 2017. Here, we present 3-D P and S wave velocity models for central Oklahoma up to 35-40 km depth.

Pg and Sg velocity models are combined to characterize the rock properties by estimating V_P/V_S and Poisson's ratio. We integrate the velocity data with regional gravity and magnetic data as well to interpret the shallow and middle crustal velocity anomalies. We interpret presence mafic intra-basement layering in the upper crust possibly of basaltic composition. We find high Pg velocity (> 7 km/s) along with high (>1.8) Poisson's ratio for the lower crust throughout the area investigated, which suggests a mafic lower crust. The high velocities support previously established models which posit that the lower crust of the Southern Granite-Rhyolite province was derived from melting of older crust.

High Resolution 3D Shear Wave Velocity Model of Salt Lake Valley via Joint Inversion of Rayleigh Wave Ellipticity and Phase Velocity From the Magna Aftershock Nodal Array

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We deployed 168 three-component nodal geophones across Salt Lake Valley between March 18 and April 30 in 2020 in response to the M5.7 Magna earthquake. In this study, we aim to refine the community velocity model of Salt Lake Valley using surface wave measurements from the nodal array and 49 station regional network. For each station, we measure reliable Rayleigh wave ellipticity or H/V ratios between 10 and 20 sec period based on the direct surface waves observed following the March 31, 2020 M6.5 Idaho earthquake. We show that the measurements can be further extended down to 5 sec by cross-correlating the Idaho earthquake coda. Overall, the observed Rayleigh wave H/V ratios are clearly correlated with the expected basin structure where low H/V ratios are observed in the mountainous area and high H/V ratios are observed within the valley in particular area between the East Bench fault and West Valley Fault zone. Homogeneous phase velocity measurements between 5 and 20 sec period for the entire study area are also obtained to provide additional constraints to the deeper structure. By utilizing the complementary sensitivity of the Rayleigh wave phase velocity and H/V ratio measurements, we constructed a high-resolution 3D Vs model of the Salt Lake Valley. Our model provides better Vs constraints compared with the current community velocity model, which was constructed from gravity, active seismic and borehole data. A high-resolution basin model is critical to understand the basin formation, fault system and seismic hazard in the region.

Incorporating Realistic Near-surface Structure Into the Cascadia Seismic Velocity Model for 3D Earthquake Simulations

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The U.S. Geological Survey's 3-D Seismic Velocity Model for Cascadia is used for a variety of research topics, including 3-D earthquake simulations and seismic hazard assessment in the Pacific Northwest. However, the current version of the Cascadia model has a minimum shear wave velocity of ~600 m/s and, therefore, does not include realistic near-surface structure. In this study, we develop functional forms for the depth-dependent shear wave velocity (Vs) as a function of time-averaged Vs in the top 30 m from hundreds of regional Vs profiles. Separate functional forms were produced for sites located on fill and alluvium, sites within the Puget Lowland and rock sites outside of the Puget Lowland. We apply these generalized Vs profiles to the Cascadia model to approximate more realistic shallow (<1 km depth) seismic velocity structure. To evaluate these updates, we run linear 3-D numerical simulations of the 2001 M6.8 Nisqually earthquake in Washington State and compare the output to recorded ground motions. Results show significant amplification of short-period ground motions (< 1 s) at soft soil sites in the Seattle Basin compared to stiff soil sites in the basin, as was observed during the Nisqually earthquake. We also develop synthetic ground motions for several hypothetical crustal earthquakes (M6-7) occurring on the Seattle Fault that vary in rupture area, slip distribution, hypocenter and rupture velocity. We then evaluate how near-surface material interacts with the response of the Seattle Basin to enhance ground motion amplification. This work demonstrates the importance of incorporating realistic near-surface structure into regional seismic velocity models that are used to estimate high frequency ground motions from simulated earthquakes.

Mapping Los Angeles Basin Depth With Converted Seismic Phases

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Sedimentary basins trap and amplify earthquake ground shaking. One important parameter of basin structure is the depth to basement, which for the densely populated Los Angeles basin is critical for estimating urban seismic hazard. The Community Seismic Network-Los Angeles Unified School District (CSN-LAUSD), a strong-motion network of 400 low-cost accelerometers located in schools in the Los Angeles region, provides a good opportunity for studying the detailed basin structure. We measure the differential travel times between direct S and converted SP phases recorded by the CSN-LAUSD network for a few deep earthquakes and map the Los Angeles basin depth using 3-D ray tracing with the community velocity model. The resulting pattern shows the deepest basin reaches 10 km, which is consistent with the results from seismic tomography and gravity surveys but provides an independent constraint with denser data coverage.

Distributed Deformation from Surface Fault Rupture

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Robb Moss, California Polytechnic State University (rmoss@calpoly.edu); Steve Thompson, Lettis Consultants Inc. (thompson@lettisci.com); Chris Milliner, Caltech (milliner@caltech.edu)

Distributed Deformations for Dip Slip Events Within PFDHA

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Our team has been working with both the FDHI and SURE databases over the last year and a half to better understand how to forecast distributed deformations in PFDHA for dip slip events. In addition to the statistical results, analytical results are presented that help bound the problem. The key aspects for implementing distributed deformations in our PFDHA approach include; probability of non-zero distributed deformations along strike, probability of exceedance with distance from strike, the relationship between magnitude and distributed deformations and the ratio of distributed to principal deformations as a function of distance from strike. These will all be discussed for both Reverse and Normal, highlighting the difference between the two mechanisms.

Distributed Fault Displacement Hazard Assessment at a Critical Facility in Southern California: Lessons Learned From Comparing Site Data to Empirical Models for Probabilistic Hazard Analysis

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In probabilistic hazard analysis of distributed faulting, the most vexing term is the conditional probability of rupture at a site. Current models rely on empirical datasets of post-earthquake rupture mapping and aggregating this information into a probability that, given an earthquake of magnitude *m* occurs and produces principal fault rupture past a site, a distributed rupture will occur at a distance *r* from the principal rupture on the site that has a footprint of size *z*. Scarcity of empirical datasets, concerns about completeness of mapping for datasets that are available and the absence of explanatory variables other than magnitude, distance and site size, are reasons for concern about how well these models perform. The distributed fault displacement model of Petersen et al. (2011) was tested against site-specific geological and geotechnical data at a coastal facility in southern California that is located adjacent to the strike-slip Newport-Inglewood fault zone. A well-defined, early Holocene stratigraphic horizon that separates sandy alluvium and estuarine deposits underlies the 500-m-long and 1000-m-wide facility and was mapped based on hundreds of closely-spaced CPTs and several boreholes. Using this early Holocene marker horizon and overlying stratigraphy we interpreted several minor faults across the site and developed three categories of fault hazard zones that may be used for engineering evaluation and design of on-site structures such as buildings, tanks and pipelines. When comparing probabilistic fault displacement hazard curves based on the site data against published models, we find that the empirical models underpredict the hazard based on the underestimation of the conditional probability of rupture. We conclude that existing empirical models should be applied to a project site with great caution and with broad uncertainties, and every opportunity to collect site-specific data should be strongly considered.

Asymmetrical Surface Rupture Width and Dependence on Shallow Fault Geometry and Topographic Slope in a }100-Year-Old Reverse Faulting Rupture, Kyrgyzstan

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Fault geometry plays a significant role in controlling the width and distribution of surface deformation, which is often expressed asymmetrically across dip-slip faults. Detailed surface rupture distributions for reverse-faulting earthquakes number less than two dozen, so all individually identifiable ruptures significantly add information to our understanding of fault displacement hazards. We collected and analyzed centimeter-scale photogrammetric surveys over 5 km of greatest surface expression of one of the largest earthquakes to have struck within the continents, the M7.8–8.2 1911 Chon-Kemin earthquake, Kyrgyzstan. The surface rupture of this earthquake is well preserved, which permits us to produce detailed maps of secondary faulting around the main rupture scarp which is up to 10 m high. Notably, extensional structures of a variety of scales attend most lengths of this primarily reverse-faulting rupture, revealing shallow kinematics that are varied but broadly associated with fault dip and in particular shallow changes in fault dip.

In places where the fault attains a steep dip, as indicated by a roughly linear surface trace across varied topography, the fault zone narrows to a concentrated set of deep scarp-crest fissures tens of meters wide. Where the dip of the apparently seismogenic fault shallows, extensional fissures in the hanging wall form hundreds of meters to 1–1.5 km into the hanging-wall, suggesting a substantial anti-listric geometry of the main reverse fault. In places, the surface of the principal reverse fault is actually "overturned"—shallowed to beyond horizontal, with a dip approaching the slope of the alluvial surfaces it has ruptured, even though the deeper dip is opposite. These structural relationships show that the topographic slope of high-relief faulted mountainfronts plays a role in shaping surface rupture geometry and that surface rupture zone width may be related to observable fault scarp geometries.

Role of Fault Maturity on the Relationship Between Surface Displacement and Rupture Length

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Magnitude-length (or area) relationships (MLRs) of faults are intrinsically linked to the physics underlying earthquakes and are relevant to seismic hazard in several ways, but are still poorly constrained. MLRs are a key component underlying the fault characterization used in seismic hazard analyses and they have an even more direct impact on probabilistic fault displacement hazard analyses (PFDHAs). The issue is also critical in properly setting-up rupture models for ground motion and displacement simulations. It is in the context of such modeling for PFDHA that we developed the present study.;

Since Scholz (1982) noted that fault ruptures can continue to increase with lengths (L-model), scientists have proposed theories and models to provide an explanation for that observation. In this study, we build on previous work and explore the value of considering fault maturity (as expressed through paleoseismic information) in improving the fit of models to observed fault displacements. We first aggregate a dataset of fault displacement, surface rupture length and paleoseismic slip rate from existing databases. We then develop a physics-based surface rupture model modified from Shaw (2013) to incorporate a term of slip-rate-related stress drop. We then perform a regression analysis that considers observational uncertainties. We find that the stress drop has a power-law relationship with the slip rate, with a negative exponent implying that a mature fault is likely to release a lower stress level than an immature fault. This relationship is then verified against seismological studies, lab experiments and numerical simulations. We also find that the ratio between the average surface and deep displacements increases with the slip rate (fault maturity) implying that a mature fault has a higher likelihood of rupturing the surface. We present our results to date as a path forward to quantifying maturity (through proxies) and its impact on data-consistent simulation modeling.

Quantifying Near-field Ground Displacements in Historical Normal Earthquakes Using Optical Image Correlation

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Optical image correlation (OIC) is a powerful tool for measuring near-field surface damage close to the earthquake ruptures. While OIC is routinely applied to large strike-slip events, we use this method to measure the three-dimensional displacement produced by two surface-rupturing historic normal earthquakes. OIC detects the horizontal displacement by tracking the shift of pixels in pre- and post-earthquake imagery. To capture the full displacement, we calculate the vertical component from the difference in elevation (extracted from stereo-overlapping image pairs), while also accounting for the horizontal displacement. OIC has a sub-pixel precision and can capture dense measurements of ground displacement close to surface ruptures (where InSAR data usually decorrelates). Near-field ground displacements provide important constraints on the strain distribution within the fault core and the surrounding damage zone and offer insight into the rupture mechanics.

We investigate the displacement fields for the 1954 Dixie Valley-Fairview Peak earthquake sequence (Churchill County, Nevada, U.S.) and the 1959 Hebgen Lake earthquake (SW Montana, U.S.). These historical ruptures are documented by aerial photo surveys. However, each photo covers only a small area (~10x10 km). This creates challenges when producing a high quality internally consistent orthomosaics needed to retrieve the displacement field through correlation. To address this problem we developed a workflow that automatically generates a DEM and orthorectified image mosaic for the pre and post-earthquake periods. Analysis of the co-seismic displacement field reveals OIC-derived displacements that exceed offsets measured in the field. The discrepancy between field and OIC displacements possibly reflects deformation accommodated off the main fault trace. Investigation of both the

Dixie Valley and Hebgen Lake earthquakes reveals new information on the distribution of off-fault damage surrounding these normal faults.

Distributed Deformation from Surface Fault Rupture

Poster Session · Friday 22 April · Conveners: Robb Moss, California Polytechnic State University (rmoss@calpoly.edu); Steve Thompson, Lettis Consultants Inc. (thompson@lettisci.com); Chris Milliner, Caltech (milliner@caltech.edu)

New Constraints on the Location and Subsurface Structure of the Holocene Birch Bay Fault, Northwestern Washington, USA

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The Birch Bay fault, located in the Bellingham Basin of northwestern Washington, USA, is a 25 to 60 km long, northwest-trending structure that accommodates north-directed shortening in the Cascadia forearc. The offshore portion of the fault is well constrained by marine seismic and magnetic data. Near the Birch Bay coastline, the fault has been inferred from airborne and marine magnetic anomalies that coincide with an uplifted beach platform and offset marsh and tidal sediments. The extension of the Birch Bay fault on land and to the southeast is coarsely constrained by aeromagnetic anomalies. The fault lacks clear geomorphic expression but is co-located with a broad zone of uplift and folding in Quaternary glacial and marine sediments and underlying Eocene sedimentary bedrock, and thus has been interpreted as a blind thrust.

We present high-resolution 2D seismic reflection data acquired along three 1 to 1.5 km long profiles that provide the first images of the fault in the shallow subsurface and support an updated interpretation of its location and subsurface expression. The fault is revealed in two profiles south and west of Ferndale as a northeast-dipping main thrust with several southwest-dipping back-thrusts that cut latest Pleistocene glaciomarine and Holocene Nooksack River delta sediments. Flower-style structures are imaged to within 30 m depth and spanning a width of 300 to 500m; however, seismic reflection resolution limitations do not preclude discrete faulting closer to the ground surface. The absence of the fault in a third profile near the Birch Bay shoreline supports a southward relocation of its position. We interpret a late Pleistocene through Holocene vertical slip rate of 0.2 to 0.8 mm/year, similar to other active crustal faults within the Cascadia forearc. The fault's orientation and transpressive subsurface expression imply a significant dextral component of slip. Future work will involve ground-penetrating radar surveys to determine whether signs of fault rupture persist near the ground surface and to better characterize the attendant seismic hazard.

Paleoseismic Evidence for a Near Historic Rupture within the Seattle Fault Zone

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Holocene fault scarps on Bainbridge Island, Washington State contain evidence for multiple late Holocene ruptures of secondary faults within the hanging wall of the Seattle fault zone (SFZ). These secondary faults are possible independent sources of local seismic hazard and provide insight into the history, geometry and kinematics of rupture on the broader SFZ. In this study, we investigate the paleoseismic history of a 1.5 m-high north-facing scarp on south Bainbridge Island. A hand-excavated trench exposed north-vergent monoclinally folded strata of the Tertiary Blakely Harbor Fm., Vashon-age glacial till, and post-glacial lacustrine deposits. Holocene colluvium associated with two paleosols infills a structural trough at the northern end of the trench and records at least two earthquakes. The most-recent earthquake raised a former intertidal sand flat, preserved on the western shore of south Bainbridge Island, which is inset into the marine terrace raised by a larger (M7+) earthquake on the main thrust of the SFZ ~1 ka yrs ago; indicating that the most-recent earthquake (MRE) occurred <1,020 cal. yrs B.P. Dendrochronology of submerged tree snags in a scarp-dammed pond east of the trench suggests that the trees died circa 1820, possibly as the result of the scarp damming the pond during the MRE, indicating a near historic earthquake within the SFZ. Preliminary Bayesian geochronologic modeling using radiocarbon ages of charcoal samples collected from horizons above and below the lower paleosol in the trench further indicate that the penultimate earthquake occurred between 16,172 – 10,486 cal. yrs B.P. Our observations provide supporting evidence to the hazard potential of these surface deforming secondary Holocene faults within the SFZ and extend the record of rupture within the SFZ to the early Holocene.

Diversity, Equity and Inclusion in Seismology

Poster Session · Wednesday 20 April · Conveners: Anika Knight, UNAVCO (anika.knight@unavco.org); Mo Holt, University of Illinois Chicago (mmholt@uic.edu); Kevin Kwong, University of Washington (kbkwong@uw.edu); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

A Summary of Existing Resources and Roadmap for the Hazards Equity Working Group of the American Geophysical Union's Natural Hazards Section

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The Hazards Equity Working Group (HEWG), founded in 2020 by the American Geophysical Union's Natural Hazards Section, seeks to address issues of equity and justice in the study of earthquakes, tsunamis and other natural hazards. This effort focuses on (1) improving diversity, equity and inclusion within the hazards research community and (2) increasing the availability and uptake of research addressing matters of social vulnerability to these hazards. Social vulnerability refers to disproportionate impacts due to personal or social attributes such as race, income, gender, disability status, sexual orientation, spoken languages or family structure. HEWG has undertaken a survey of existing resources, such as webinars and documentation, of which we will present a summary with emphasis on seismology. We find there is a strong push within the scientific community for action towards goal (1), but fewer materials and less systemic organization for the more niche goal (2). HEWG is therefore well-positioned to scope an action plan, especially for goal (2), in coordination with other groups.

We present our 5-year vision with a call for membership and action. Progress can be made toward goal (1) through actions including evaluating prejudicial aspects of hiring/retention policies, mandating implicit bias/discrimination training, improving mentorship and requiring somewhat controversial 'broader impacts' verbiage in proposals. Goal (2) can be approached through activities like partnerships between social and physical scientists, building knowledge around cultural competencies, introducing social vulnerability training in geoscience curriculum, evaluating social vulnerability considerations in funding proposals for physical scientists, making open access publication the gold standard for academic productivity and fostering relationships between academia, practitioners and communities such that scientific inquiry is co-designed and addresses sustainable end user goals.

Working To Ensure a More Diverse, Equitable, Inclusive and Accessible Workplace: DEIA Actions Within the US Geological Survey's Alaska Region

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Federal research agencies such as the U.S. Geological Survey (USGS) have similar systemic inequities and diversity demographics as are commonly found in academic institutions. Out of concerns over the lack of diversity within working environments, a group from the USGS' Alaska Region (one of seven USGS Administrative Regions) took part in the 2021 "Unlearning Racism in GEoscience" (URGE) curriculum with support from Alaska Region management. At the end of the URGE curriculum, management met with participants to review recommendations and discuss next steps. One outcome was the formation of a Diversity, Equity, Inclusion and Accessibility (DEIA) Steering Committee (SC), along with the funding of a quarter-time DEIA coordinator position. The SC, which consists of the authors of this abstract, has met regularly since August 2021 to identify, prioritize and develop actions for addressing systemic inequities and barriers within our work environment. Initial priority areas include hiring and mentorship/onboarding. For hiring, we have taken a systematic look at all aspects of the hiring process and identified a number of changes to implement, including: working on expanding the diversity of qualified applicants pools through more intentional outreach, internships and staff participation in conferences that center on historically underrepresented groups; expanding the places where jobs are advertised; and putting measures in place for mitigating implicit bias during the hiring process. For mentoring, we identified a need to improve the onboarding experience for new employees and are in the initial stages of designing a mentorship program that incorporates best practices including mentor training, facilitated matching of mentor/mentee pairs and establishing cohorts. We are in the early stages of implementation in each area. Our next priority area will be examining physical and psychological safety in the office and in the field through a DEIA lens.

Earthquake Source Processes at Various Scales: Theory and Observations

Oral Session · Thursday 21 April · 8:00 AM Pacific

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Valerie Sahakian, University of Oregon (vjs@uoregon.edu); William Ellsworth, Stanford University (wellsworth@stanford.edu); Taka'aki Taira, University of California, Berkeley (taira@berkeley.edu)

The SCEC/USGS Community Stress Drop Validation Study Using the 2019 Ridgecrest Earthquake Sequence Data

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We present preliminary comparisons from the SCEC/USGS community stress drop validation study using the 2019 Ridgecrest earthquake sequence, in which researchers are invited to use a common dataset to estimate earthquake stress drop. We seek to understand the physical controls and methodological reasons for similarity or differences in stress drop estimates, so that they can be used more reliably by the earthquake science community. The common dataset consists of 2 weeks of earthquakes following the 2019 Ridgecrest M6.4 earthquake, including nearly 13,000 events of M1 and greater, recorded on stations within 100 km. As a community study, all are invited to join; more information can be found at https://www.scec.org/research/stress-drop-validation.

At the November 2021 SCEC workshop, attended by over 100 participants from 14 countries, 11 research groups submitted initial results using the common data set. The analytical approaches used include spectral decomposition/generalized inversion; spectral ratios or eGf in the frequency domain; source time functions or eGf in the time domain and other methods such as ground-motion and single-station approaches. Direct comparison reveals considerable scatter, yet stronger correlations between results using similar methods. We identify a set of 22 events of M3 to M4 that were used in at least 8 analyses; some of these events show significantly reduced inter-method scatter than others. Since the workshop, researchers are refining results to focus on a subset of the data: 50 select events of M2+, including the 22 previously identified, representing a range of depths, mechanisms and azimuths. We also consider uncertainty in other parameters, such as moment and earthquake depth, the effects of variable paths and other considerations such as how researchers considered record quality control.

Spectral Scaling Comparison and Validation Between Coda and GIT Spectra for Central Italy and Ridgecrest, CA (3.3<Mw<7.1)

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The coda magnitude method of *Mayeda and Walter* (1996) provides stable source spectra and moment magnitudes (M_w) for local to regional events from as few as one station that are virtually insensitive to source and path heterogeneity. We applied this method to two active regions, central Italy and the southern Sierra Nevada and compare against results derived from the data driven, generalized inversion technique (GIT). We find excellent agreement and both allow for consistent measures of M_w over a broad range of event sizes rather than relying on empirical magnitude relationships that tie M_L to M_w. Coda has the advantage of requiring much fewer events and stations for calibration and routine measurement. Additionally, we use independent ground-truth source spectra constraints to break the path and site trade-off, as well as *not* imposing a regional source scaling assumption or assuming a fixed stress drop for Green's function events. Both approaches and regions show an increase in apparent stress with increasing magnitude to roughly M_w 5.5, then becomes constant. Events below this threshold have significantly more scatter, perhaps a consequence of post-mainshock stress equalization. We use the new Coda Calibration Tool (CCT) that stems from a multi-year collaboration between the US NDC and LLNL scientists, as well as collaboration with other institutions who are helping to evaluate and test the code with the goal of developing a fast and easy Java-based, platform independent coda envelope calibration and processing tool. We present an overview of CCT focusing on two large sequences, the Amatrice-Visso-Norcia (Italy) and Ridgecrest (CA) sequences. Calibration examples and CCT are freely available to the public on GitHub (https://github.com/LLNL/coda-calibration-tool). The tool can be used in routine processing to obtain stable source spectra for M_w, radiated seismic energy, apparent stress, corner frequency, and source discrimination on event type and/or depth.

Stress Estimations of Moderate Earthquakes During the Ridgecrest Earthquake Sequence

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Ji and Archuleta (2022) reported that for Mw 5.3-6.9 crustal earthquakes in active tectonic regions, the non-self-similar scaling relations of fault geometry (Leonard, 2010) and their double corner source spectrum constrained by strong ground motion parameters (JA19_2S, Ji and Archuleta, 2020) can be reconciled with magnitude independent static and dynamic stress drop, both about 3MPa. If the same conditions hold for M<5.3 earthquakes, apparent stress should decrease with magnitude while the aspect ratio of the fault plane would increase though the static and dynamic stress drop would remain constant. We verify these predictions using M>4 earthquakes during 2019 Ridgecrest earthquake sequence. Three estimates of stress change are investigated. First, the initial amplitude of velocity seismograms is often small, but after a brief period the amplitude grows approximately linearly. The latter stage was named "breakaway" phase (Ellsworth and Beroza, 1995). The slope of the growth is related with the lower bound of a dynamic stress drop in the region where these events nucleate and grows as a self-similar circular dynamic model (Kostrov, 1964; Boatwright, 1980). Second, the same velocity records are used to estimate apparent stress (after carefully correcting the path and site effects. Third, for the earthquakes with good empirical Green's functions, the subjective-oriented finite-fault inversion (Adams et al., 2019) is used to explore the uncertainty range of finite-fault based static stress drop.

Characterization of Earthquake Swarms and Ruptures to Reveal Driving Mechanisms

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Detailed analysis of well-recorded earthquake sequences, tectonic and induced, has the potential to reveal the relative influence of multiple processes on earthquake nucleation and rupture propagation. High precision relocations enable mapping of seismicity migration rates, indicative of fluid or aseismic forcing. Combined with focal mechanisms, the relocations reveal the active structures and their relative stress states. Source analysis provides information about the finite rupture extents and rupture directions, which are needed to constrain earthquake interactions and triggering. Previous work has suggested that the stress drop, rupture propagation direction and even source complexity may depend on local conditions resolvable by seismicity characteristics. Here we focus on a well-recorded induced earthquake sequence in central Oklahoma, that started in 2014 and lasted over 18 months. Chen et al. (2018) relocated over 900 earthquakes (largest M4.3) and found strong temporal association between seismicity migration behavior and nearby disposal well injection rates. Chen & Abercrombie (2020) investigated the spatial variation of stress drop using a spectral decomposition method. We calculate stress drop and rupture directivity for the best-recorded earthquakes using an empirical Green's function technique and combine the results with the previous observations of the earthquakes and seismicity. We compare our results with those from Chen & Abercrombie to understand the uncertainties better. We investigate whether the rupture directivity of the larger earthquakes is related to the observed directions of seismicity migration. We also consider whether the directivity, stress drop and source complexity are related to the relative stress on the fault plane, or the local fault structures. We compare our results to previously published results and investigate the implications for earthquake rupture nucleation and propagation.

Earthquake Arrest and Stress Overshoot Affect Observed Scaling of Breakdown Energy and Source-time Functions

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Most earthquake scaling observations are consistent with a model of an earthquake that is an expanding circular shear crack with a small nucleation process, constant rupture propagation speed and an arrest that ultimately determines the final size of the earthquake. However, seismologically inferred breakdown energy is observed to scale with slip and varies by at least four orders of magnitude. This scaling is often attributed to enhanced fault weakening that occurs with continued slip, possibly caused by thermal pressurization. Our work explores earthquake scaling relations through a suite of 3D dynamic rupture simulations and their seismically observable properties—moment, stress drop, apparent stress and seismically observed breakdown energy. The models vary in size to produce a range of earthquake magnitudes; however, numerical resolution, the nucleation procedure and fault friction properties, including fracture energy, are kept constant across all scales. The models are essentially self-similar, conform to common earthquake scaling relations and demonstrate that breakdown energy scaling can occur despite constant fracture energy and does not require thermal pressurization or other enhanced weakening. Instead, breakdown energy scaling occurs simply due to scale-invariant stress drop overshoot, which occurs in crack-like ruptures when a fast-propagating rupture front arrests but parts of the fault continue to slip. Our results show that seismically observable breakdown energy may be affected more directly by the overall rupture mode—crack-like or pulse-like—rather than from a specific slip-weakening relationship. This helps explain inferences of negative-valued breakdown energy (commonly ignored) as resulting from negative overshoot (undershoot), related to pulse-like ruptures. The dynamic rupture models also provide insights into how earthquake arrest affects source-time functions and explains observations of linear growth of moment-rate.

Are Most Earthquakes' Non-double-couple Components Artifacts?

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Earthquake moment tensors can be decomposed into double-couple components describing slip on planar faults and non-double-couple (NDC) components. NDC components can arise in three ways. Some appear to be intrinsic, indicating complex source processes differing from slip on a fault for earthquakes in specific geologic environments, notably volcanic areas. Others are additive, reflecting the combined effect of double-couple sources on multiple faults with different geometries. Alternatively, they may be artifactual results of the moment tensor inversion. Combining moment tensors from three global and four regional catalogs for 2016-2020 provides a dataset of NDC components of 12,856 earthquakes with 2.9 < Mw < 8.2 in various geologic environments. The NDC components vary only slightly with magnitude, with a mean deviation from a double-couple source of around 20%. The consistency suggests that most NDC components do not reflect rupture on multiple faults, which has been observed only for larger earthquakes. Similarly, there are only small differences in NDC components between earthquakes with different faulting mechanisms, or in different geologic environments. These consistencies suggest that most NDC components components are not intrinsic due to complex source processes that are often assumed to be most likely in volcanic and thus extensional areas. Hence it appears that for most earthquakes, especially smaller ones, the NDC components are artifacts, in accord with numerical experiments showing that they arise when the Earth model used for the inversion differs from that used to generate synthetic waveforms.

S/P Amplitude Ratios Derived from Single-component Seismograms and Their Potential Use in Resolving Focal Mechanism Complexity of Micro-earthquake Sequences

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Focal mechanisms, which reflect the sense of slip in earthquakes, provide important constraints for understanding crustal tectonics and earthquake source physics, including the interactions among earthquakes during mainshock-aftershock sequences or seismic swarms. Focal mechanisms of small (M ≤ 3.5) earthquakes are usually determined by first-motion P-wave polarities, sometimes supplemented by S/P amplitude ratios. However, focal mechanisms of such events can be difficult to reliably constrain, particularly with sparse recording networks or very-small-magnitude events. Here, we describe a method for deriving S/P amplitude ratios from P/P and S/S amplitude ratios measured on individual seismic components (i.e., east, north or vertical) between pairs of nearby events, as is often performed during correlation-based earthquake detection and relocation. These measurements can be transformed into relative S/P amplitude ratios, or they can be combined with a smaller number of traditional S/P amplitude ratios to provide a single-component estimation of full S/P ratios, even for low signal-to-noise-ratio events not routinely cataloged and not amenable to traditional S/P ratio processing. This approach has the potential to greatly expand the applicability of S/P amplitude ratios, providing improved resolution of focal mechanism complexity for spatially concentrated seismicity sequences.

Utility of Seismic Source Mechanisms in Mining

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The general theory for the description of seismic sources is briefly discussed. The effect of excavations on seismic radiation is considered. Expressions for seismic source mechanisms in terms of the geometrical and mechanical parameters of source processes are provided for the following cases: fault slip and shear failure in a confined environment, dynamic stress fracturing around a tunnel, rock fall, landslide and collapse. A classification of seismic events in mines based on source mechanisms is introduced. The classification separates blast-, slip- and crush-type events. Various approaches of analysis of source mechanisms involving forward modelling and inversion are discussed. The following examples demonstrating the utilization of source mechanisms in mining are presented: forensic analysis of damaging seismic events, assessment of the increase in the depth of failure for dynamic stress fracturing around tunnels and its duration, examination of the rockmass deformation regime, assessment of deformation around tunnels using crush-type events, identification and parameterization of weak geological structures, stress inversion from slip-type events. Finally, the requirements for seismic data to ensure high-quality source mechanism solutions are briefly reviewed, and future challenges in the interpretation and utilization of seismic source mechanisms in mines are speculated on.

Because Small Earthquakes Matter: Lessens Learned From Extensive Testing of CMT Inversion for Regional Earthquakes

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Source studies of small to moderate earthquakes are essential to improve insights into active tectonic processes in study areas with low seismic activity and in case of short deployment times of seismic networks. Our study relies on the probabilistic bootstrap-based inversion tool Grond and the temporarily densified AlpArray seismic network (>600 stations operated in 2015-2019), to develop and apply methodological tests tackling various pitfalls of full waveform based CMT inversions. These aspects include: (1) quality checks of seismic stations prior to the inversion (via the AutoStatsQ toolbox), (2) tests of moment tensor resolution depending on frequency range and input data type, (3) the occurrence and resolution abilities of non-DC components and (4) the influence of gaps in the azimuthal station distribution.

We present a full-waveform based workflow dedicated to improving the assessment of uncertainties of seismic source studies of small to moderate earthquakes. Applying this workflow to the AlpArray helped lower the magnitude threshold and improve the stability of regional CMT inversions. We propose to conduct similar studies prior to MT inversions for any challenging dataset to avoid the misinterpretation of poorly resolved patterns.

Detection Limits and Near-field Ground Motions of Fast and Slow Earthquakes

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We investigate theoretical limits to detection of fast and slow seismic events and discuss spatial variations of ground motion expected from an synthetic family of M6 earthquakes at short epicentral distances. The performed analyses are based on synthetic velocity seismograms calculated with the discrete wavenumber method assuming seismic velocities and attenuation properties of the crust in Southern California. The examined source properties include magnitudes ranging from M -1.0 to M 6.0, static stress drops (0.1-10 MPa), and slow and fast ruptures (0.1-0.9 of shear wave velocity). For the M 6.0 events we also consider variations in rise times producing crack- and pulse-type events and different rupture directivities. We found slow events produce ground motions with considerably lower amplitude than corresponding regular fast earthquakes with the same magnitude, and hence are significantly more difficult to detect. The static stress drop and slip rise time also affect the maximum radiated seismic motion, and thus event detectability. Apart from geometrical factors, the saturation and depletion of seismic ground motion at short epicentral distances stem from radiation pattern, earthquake size (magnitude, stress drop) and rupture directivity. The rupture velocity, rise time and directivity affect significantly the spatial pattern of the ground motions. The results can help optimizing detection of slow and fast dynamic small earthquakes and understand the spatial distribution of ground motion generated by large events.

Bayesian Dynamic Source Inversion With Rate-and-state Friction—Unified Seismic and Postseismic Rupture of the 2014 South Napa Earthquake

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The 2014 South Napa earthquake was followed by an unusual amount (up to 1m) of shallow afterslip and by a series of ~100 aftershocks located below the coseismic rupture. The afterslip occurred mainly to the south of the coseismic rupture; lithological transition from sediments in the south to sedimentary rocks in the north was suggested to explain the spatial distribution of coseismic and postseismic slip (Floyd et al., 2016). We carry out a Bayesian inversion using our code FD3D_TSN (Premus et al., 2020) to infer spatially varying controlling frictional parameters and stress on the fault. The resulting dynamic models of the earthquake and consecutive afterslip are based on the fast-velocity-weakening rate-and-state friction and constrained by a dataset from close seismic and geodetic stations. Models fit the measured data well and agree with published kinematic models, capturing main features of the source: the rupture propagating upwards and northwards with two main slip patches and the position of the shallow afterslip patch. We observe horizontal heterogeneity of dynamic parameters in the top 5 km of the fault, corroborating the hypothesis about the local lithology. Transition zone between the co- and postseismically rupturing areas are characterized by lower prestress and more velocity-neutral friction (b-a close to zero). The strengthening rheology is more pronounced in the shallow postseismic area (b-a~-0.01) than in the shallow coseismic area (b-a~-0.005). In our models, we further note a presence of a velocity-strengthening zone cutting through the weakening seismogenic part of the fault in the depth of ~7.5 km, generating a larger afterslip. Its existence is supported by the occurrence of off-fault aftershocks concentrated around the area whose decay rate time evolution fits well that of the modeled fault stressing rate.

Source Spectral Properties of Earthquakes in the Yellowstone Caldera

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The mechanisms responsible for earthquake swarms have been elucidated with increasing resolution; they are driven by either aseismic slip or the migration of fluids through a preexisting fault network. However, it remains unclear how these transient phenomena affect the source processes of the triggered earthquakes. We apply a spectral decomposition approach to analyze P- and S-wave spectra of a few of the most intense swarms recorded in the Yellowstone caldera. By leveraging recent advances in deep learning to obtain precise S-wave picks, we estimate source properties using both P- and S-wave spectra for a significant fraction of the recorded events. We analyze the Mw 5.2, 2016, Borrego Springs earthquake sequence in the San Jacinto fault zone, using the same approach to establish a baseline for comparison. Our results suggest swarm earthquakes have consistently smaller radiated energy ratios than earthquakes on mature faults. We interpret the differences in radiated energy ratios as resulting from volumetric components in the source of swarm earthquakes. As hydrothermal fluids move through the system, they may cause the opening or closure of cracks in the source region.

Constraining Kinematic Rupture Scenarios of an Mw 6.2 Earthquake in Central Italy

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The region of Central Italy is well known for its moderate to large earthquakes. Events like L'Aquila (Mw 6.1, 2009), Amatrice (Mw 6.2, 2016) and Norcia (Mw 6.5, 2016) arouse great concern and motivate ground motion modeling to provide insights on source-related complexities.

We utilize a hybrid integral-composite kinematic rupture model by Gallovič, and Brokešová (2007). The Green's functions are computed in 1D crustal velocity models, including site-specific 1D soil profiles for selected stations up to 10 Hz. We optimize the model parameters (rupture velocity, parameter a related to high-frequency radiation and kappa describing the attenuation at the site) by the grid-search method using spectral acceleration bias between synthetic and recorded data of the Amatrice earthquake at reference stations with negligible site effects. For the best-fitting model, we compute synthetic seismograms at 400 phantom stations considering two different crustal velocity models, following the major geological features of the area. Results match regional non-ergodic GMM by Sgobba et al. (2021) within 50 km for periods 0.2 - 5 s.

Furthermore, we perform ground motion prediction for a hypothetical future event of the same magnitude. We create up to thousand different scenarios varying source parameters: nucleation point, rupture velocity, parameter a, fault size and slip distributions. We evaluate spectral accelerations at specific periods for each rupture scenario and compare them with the regional GMM. We apply statistical mixed-effect modeling to i) discriminate the within- and between-event variability and ii) quantify the effects of source model parameters on the modeling. We demonstrate trade-offs among some source model parameters. Namely, the so-called stress parameter, combining the rupture velocity, parameter a and fault size, explains the majority of the ground-motion variability. Comparison of the synthetic between-event variability with the empirical one limits the variability of the stress parameter and thus constrains the scenario earthquakes for physics-based seismic hazard assessment.

Investigation of the Induced Earthquake Sequence Near Stanton, Texas

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The Midland Basin of west Texas has been experiencing increased levels of seismicity that are hypothesized to be due to wastewater disposal by injection from the unconventional oil fields in the area. The largest earthquakes to date occurred near the town of Stanton and include a Mw 4.0 on December 31, 2020 and a Mw 4.5 on December 28, 2021. The earthquakes occurred in an area with numerous horizontal production wells and several deep injection wells. In this study we determine precise earthquake locations for the sequences using a combination of surface and borehole seismic stations. We processed continuous seismic data using a machine learning phase-picker, PhaseNet, and back-projection-based phase arrival time associator to creating a catalog for Stanton sequence. We also modified a conventional location program to use borehole stations located below a high-velocity salt layer in a 1-D velocity model constructed from nearby well log data. Our preliminary findings show that focal depths of Stanton sequence lie in the shallow basement between 4 km and 7 km. Hypocenters define an E-W striking plane that matches the left-lateral fault plane of the moment tensor solutions of the two largest earthquakes. This fault plane is optimally oriented for movement with only a small pressure perturbation in the local stress field. Foreshocks of both M 4+ earthquakes also locate on or near the same planar fault structure. Stanton sequence highlight the importance of continuous local earthquake monitoring for the detection of emergent fault activation and its evolution.

Stress and Fluid Earthquake Triggering During the 2015–2017 Pamir Earthquake Sequence

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A sequence of three large (M_W 7.2–6.4) and several moderate (M_W 4.4–5.7) earthquakes struck the Pamir Plateau and surrounding mountain ranges of Tajikistan, China and Kyrgyzstan in 2015–2017, activating numerous segments of an extended regional fault network. Two local temporary seismic networks recorded the fore-, main- and aftershocks with good azimuthal coverage, allowing us to locate 11,784 seismic events and determine the moment tensors of 35 earthquakes. The earthquake pattern shows that faults were activated subsequently at increasing distances from the initial M_W 7.2 Sarez earthquake. All mainshock areas but the initial one exhibited foreshock seismicity, which was not modulated by the occurrence of the earlier earthquakes.

We tested if the subsequent mainshocks have been triggered by transfer of static Coulomb stresses through earthquake cascades. Stress transfer modelling using published distributed fault slip models, postseismic InSAR displacement rate maps and our moment tensor solutions indicates that stress-triggering occurred over distances of ≤90 km on favorably oriented faults with Coulomb stress changes as small as ~15 kPa. The second largest M_W 6.6 Muji earthquake occurred despite the repeated relaxation of its fault during the sequence, seen in an overall Coulomb stress reduction of ~10 kPa. The third largest M_W 6.4 Sary-Tash earthquake shows a Coulomb stress increase of only ~5 kPa. To explain the significant accumulation of M_W 6+ earthquakes on adjacent fault zones despite low transferred stresses, we reason that the initial mainshock may have increased nearby fault permeability, which facilitated fluid migration into the mature fault network and eventually triggered the large earthquakes through pore pressure increase.

Stress-strain Characterization of Complex Seismicity Along California Faults

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Earthquake ruptures and seismic sequences are the inelastic strain response to tectonic stress fields. We develop a physics-based probabilistic model to characterize stress-strain fields using moment measures of mechanism complexity. Distributions of focal mechanisms in seismic sequences and earthquake ruptures are used to estimate the ratio of the Aki seismic moment to the total moment and the partitioning of the moment tensor field over an orthonormal basis of five deviatoric mechanisms. These moment measures of complexity are then used to estimate the principal-stress directions, a differential stress ratio (R) and a stress-strain sensitivity parameter (κ). Large values of κ indicate high-stress concentration and, thus, low complexity. We quantify the effect of focal mechanism uncertainty on the moment measures using a hierarchical Bayesian model. We apply the model to characterize the complexity of stress-strain fields of seismicity in California. We show that the observed complexity is related to evolutionary geologic variables such as the cumulative slip in the fault. For example, the seismicity along the San Andreas Fault in the Parkfield and Loma Prieta sections, which have over 150 km of cumulative slip, shows significant stress-strain sensitivity (κ=8±1.1), i.e., low complexity. In contrast, faults in the Mojave Block with less than 5 km of cumulative slip show a low sensitivity (κ=3±1.5). The stress field before the Ridgecrest earthquake of 2019 shows high complexity (κ=3±2), while the aftershocks show less complexity with κ=6±2, indicating that the aftershocks are more aligned with the mainshocks than the background seismicity.

High-frequency Emissions From Stimulation Microearthquakes in the Ambient Crust

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We report and provide a simple Haskel model for multiple high frequency (200 to 800 Hz) seismograms from -1 to 2 magnitude microearthquakes induced during an EGS project in Finland. Our data come from 2 kHz recordings of 5 to 6 km deep events as received on a 12-level, 1.9 to 2.4 km deep vertical seismic profiling array. The array was located essentially above the EGS stimulation well, with lateral offsets of less than an few hundred meters. Both were in Pre-Cambrian crystalline rock. The observed velocity spectra of these events do not conform to a single slip-plane model where v(f) ~ vof/(1 + f/fo)2) and characteristic frequencies fo ~ 1/L scaling inversely with slip surface dimension L ~ 10-m/2.

In the absence of such waveform evidence for a single planar slip, we use Haskell's slip-velocity elastodynamic seismic radiation formalism to account for these signals as resulting from a zones of spatially and scale-length distributed slips associated with permeability structures. Based on well log and core data, Haskell modelling suggests these slips occur on fractures whose distributions follow power law scaling of ~ 1/k, where k is the wave number/spatial frequency. Following Haskell then, a seismic slip deformation front can in principle traverse such complex crustal volumes with a range of velocities Vslip. The mean slip velocity along with the spatial and scale distributions determines how radiation from individual slip patches combine to create a net seismic waveform. This simple model shows that our observations can be matched using a range of velocities VS/10 < Vslip < VS moving along such 1/k-scaling disturbed fracture zones. It remains to validate this approach with more sophisticated source models that include full 3-D distribution of fractures that give rise to the ~ 1/k scaling power-spectra seen in 1-D well logs.

The Mw 5.7 Pica Earthquake: A Crustal Event in Northern Chile with Large Ground Accelerations and Stress Drop

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Important crustal earthquakes in Chile are less frequent compared with interplate and intraplate events. However, even moderate-magnitude onshore crustal events can pose a major hazard due to their closer proximity to pop-

ulation centers. We study the rupture properties of a Mw 5.7 crustal earthquake that occurred in 2008 near the town of Pica, under the Central Valley of northern Chile, which was well recorded with both strong motion and broadband instruments. This event generated maximum ground accelerations of up to 0.67 g in Pica, one of the largest recorded for this type of events. Overall, its observed ground motions are larger than expected by prediction models, particularly at short periods. The mainshock rupture exhibits a large stress drop of 250 MPa, inferred via S-wave spectrum modeling, which is likely a contributing factor to its large ground accelerations. Its hypocenter was located at 33 km depth in a cold and brittle region of the crust, with an inferred 9 km long by 8 km wide rupture via Bayesian inversion of waveforms. The fault plane is striking towards the NW and dipping towards the NE, as defined by the moment tensor solution and aftershock distribution. This geometry is similar to that of crustal earthquakes occurring under the neighboring Coastal Cordillera, including the large 2020 Mw 6.3 Loa River crustal earthquake, suggesting that the Pica earthquake is under the same stress field, and likely occurred in a buried branch of the margin-perpendicular reverse faults mapped in the Coastal Cordillera. These factors indicate the possibility of more similar events occurring in northern Chile, where our recurrence estimates show that Mw ≥ 5.7 crustal events have occurred, on average, every three years.

Reexamination of the Earthquake Source Spectrum and the Inferred Source Parameters

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Aki (1967) laid the foundation for interpreting the source spectrum. Using the autocorrelation of sliprate on the fault, he determined a source amplitude spectrum that was i) proportional to seismic moment at frequencies less than a characteristic frequency k_T, ii) decreased as f^{-2} at frequencies much greater than k_T and iii) $k_T \sim M_0^{-1/3}$ (M_0 -seismic moment). Using a much different approach Brune (1970) developed a source spectrum that has same asymptotic elements as Aki's spectrum. Using conservation of energy Brune related the characteristic frequency, i.e., corner frequency f_C, to fault radius. Brune showed that the spectral slope is f^{-1} near f_C for a partial stress drop. The source spectrum for both Aki and Brune results in self-similarity of radiated energy E_R. As such the apparent stress (s_a=muE_R/M_0) is constant. Other (M_0-f_C) models of the spectrum have been developed by determining a corner frequency and fault radius, e.g., Sato and Hirasawa, 1974; Madariaga, 1976; Kaneko and Shearer, 2014. However, stress drop derived from (M_0-f_C) models can differ among them by a factor of almost 6 and differ from stress drop derived from (E_R-M_0) models. While there can be a large difference in the estimated stress drop *Ds* from (M_0-f_C) models, all such models predict nearly the same radiated efficiency h~0.5. The classic Orowan model with h=1.0 (no fracture energy) results in $Ds=2s_a$. With h~0.5, the stress drop is ~ $4s_a$. (M_0-f_C) models have only one fault dimension. For large magnitude earthquakes, particularly strike-slip, the static stress drop will depend on the fault shape (Knopoff, 1958). In Ji and Archuleta (2022), we show that our proposed double-corner frequency source spectrum (Ji and Archuleta, 2020) when combined with Leonard's (2010) regressions for fault length and fault slip predicts: constant static stress drop, constant dynamic stress drop and a single average rupture velocity for magnitudes 5.3-6.9 while the fault aspect ratio varies from 1.1 to 2.3.

Spatial-temporal Evolution of In-situ Vp/Vs Ratio in the Gofar Transform Fault Zone, East Pacific Rise

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Understanding the nucleation and arrest of earthquake ruptures is fundamental to earthquake physics and seismic hazard mitigation. The Gofar Transform Fault near the equatorial East Pacific Rise is an ideal natural laboratory for studying these processes due to its systematic and predictable seismic behaviors: its westmost segment contains two asperities that produce M 6 events every ~5 years, and these earthquakes are bounded by barrier zones that play an important role in both initiating and terminating the ruptures. In 2008, an ocean-bottom-seismograph array was deployed around the Gofar Transform Fault for a year and successfully captured a predicted M 6 event on the western asperity as well as abundant foreshocks and aftershocks. This dataset provides an unprecedented opportunity to study earthquake nucleation and arrest at oceanic transform faults. Here, we use differential P and S arrival times obtained from waveform cross-correlation to investigate the spatial-temporal variation of in-situ Vp/Vs ratio in the fault zone, which can directly reflect the poroelastic material properties of the fault zone. We find that the fault zone generally has a lower Vp/Vs ratio (~1.7) than that of a typical oceanic crust (>1.8), indicating the presence of water-filled cracks. Moreover, we find that the fault patch near the mainshock hypocenter has an abnormally low average Vp/Vs ratio, with its Vp/Vs ratio continuously increasing from ~1.5 to ~1.7 over ~8 months prior to the mainshock and then abruptly dropping to ~1.6 afterward. We also identify another fault patch in the barrier zone with a low average Vp/Vs ratio and a similar Vp/Vs ratio evolution preceding the mainshock, though with lower amplitude. In contrast, the rest of the fault zone has stable Vp/Vs ratios with no systematic changes during the observational period. Our results indicate that pore fluid likely plays an important role in regulating earthquake ruptures at the Gofar Transform Fault.

Earthquake Source Processes at Various Scales: Theory and Observations

Poster Session · Thursday 21 April · Conveners: Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Valerie Sahakian, University of Oregon (vjs@uoregon.edu); William Ellsworth, Stanford University (wellsworth@stanford.edu); Taka'aki Taira, University of California, Berkeley (taira@berkeley.edu)

A Fast Procedure to Estimate the Prevailing Rupture Propagation Direction and How It Applies to the 2016-2017 Central Italy Seismic Sequence

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We present a new approach aimed to generalize the statistical procedure proposed by Calderoni et al., (2017) to estimate the prevailing direction of rupture propagation in a given region during a seismic sequence. We apply this procedure to the strongest earthquakes (Mw ≥ 4.4) of the 2016-2017 Central Italy seismic sequence and compare our results with other studies. The method is based on the Empirical Green Function (EGF) deconvolution method. The main advantage of our method is that it is conceptually simple and fast (near real-time speeds) and can be applied to any active seismic area. Results show heterogeneity of rupture directivity along the activated fault system with a complex pattern even if most of the studied events have similar focal mechanisms. However, homogeneous pattern in rupture directivity is observed along the activated fault system and the preferred trend of the rupture propagation is in large part controlled by pre-existing structural discontinuities, i.e., the NW-SE faults. Therefore, we suggest that pre-existing structural discontinuities may control the directivity in the way that such discontinuities represent weakness zone, i.e., zones affected by a bi-material fault interface. We also discuss the possible role of fluids as a cause of bi-material and propose an interpretation of our results based on the role of fluids in the studied sequence as reported in literature.

Furthermore, we investigated a possible control of rupture directivity on the location of immediate aftershocks. We calculated the cumulative number of events, which occurred in the forward, backward and orthogonal rupture propagation direction, before and after the occurrence of events and found that for the analyzed events immediate seismicity mainly appears to be correlated with rupture directivity along the pre-existing structural discontinuities.

A New Focal Mechanism Calculation Algorithm Using Inter-event Relative Radiation Patterns

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Accurate earthquake focal mechanisms are essential for solving fault zone structure, estimating crustal stress variations, and providing reliable hazard assessments. Currently, the focal mechanisms of small earthquakes are solved using P-wave first motion polarities and/or the S-/P-wave amplitude ratios.

Because of the low signal-to-noise ratio of small earthquake waveforms and limited number of 3-component seismograms, small magnitude earthquakes have limited number of input P-wave polarities and S-/P-wave amplitude ratios. Using these limited inputs, even the high-quality focal mechanism solutions still have about 20-30° nodal plane uncertainties. To improve the focal mechanism resolution, instead of analyzing events one-at-a-time, we develop a method that utilize the inter-event relative radiation patterns to perform joint inversion of focal mechanisms of numerous events. The method uses P-wave polarities, P-wave amplitudes, and S-wave amplitudes, as well as the relative P- and S-wave amplitude ratios between neighboring events, and applies an iterative inversion algorithm to obtain initial focal mechanisms and improve the solutions of focal mechanisms that are clustered in space. The method utilizes GPU computing technology and is computationally efficient to process large data sets. We apply the method to earthquakes in the Parkfield region, California. The results show significant improvement in focal mechanism resolution and highlight the future potential for applying the method on large scale datasets and further improve the resolution of fault geometry and stress field estimation.

Analysis of the 2015 Gorkha-Dolakha (Central Nepal) Foreshocks and Aftershocks Sequence Through Transients in B Values

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The frequency magnitude distribution (b-value) is studied for the Nepal Himalaya (27.4- 28.6ºN and 84.5-86.5ºE), which is a part of the central Himalaya seismic gap and has host the 2015 M7.8 Gorkha and M7.3 Dolakha earthquake in the recent past. The analysis includes a total of 827 earthquakes from the International Seismological catalogue (ISC) recorded through 24 April 2005 to 11 May 2021. The b-value is computed for three different time intervals that includes the preshocks of the Gorkha earthquake, period between the Gorkha earthquake and the Dolakha earthquake and post Dolakha earthquake to recent times. A comprehensive mapping of spatial variations of b-value is also made for the studied region. Significant variations in the b-value are detected with b ranging from b ≈ 0.89 to 1.07. Low b-values of 0.89 ± 0.16 and 0.87 ± 0.04 is observed for the pre Gorkha and post Dolakha earthquakes in the region. On the other hand, significant increase of 18 % in b-value is observed for the period between the Gorkha and the Dolakha seismic events. The abnormal low b-values computed for the region corresponds to a low differential stresses that is due to the presence of already critically stressed zones due to past earthquakes and tectonic loading of the faults and this should be released through a major seismic event in future.

Characterization of Foreshocks for Mainshocks (Mj3.0 to 7.2) of Onshore Japan During 2001 to 2021

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We use a relatively large database of over 2000 shallow mainshocks (Mj3.0 to 7.2) for onshore Japan to search for foreshocks using the Japan Meteorological Agency (JMA) earthquake catalogue from 2001 to 2021. For the onshore region there is level of completeness for the catalog down to Mj1.0. To define foreshocks, we investigate the space-time relation of all pairs of earthquakes when a larger event follows a smaller event. We find clear peaks for the occurrence of the earlier small earthquakes within 10 days and 3 km prior to the mainshocks, which is used as our definition of foreshocks. For this study, we remove the aftershocks, earthquake swarms and possible earthquakes triggered by the 2011 Mw9.0 Tohoku-oki earthquake in order the evaluate the foreshock occurrence for the ambient conditions of regional stress. After this declustering of the catalog, we have 2,066 independent earthquakes to search for foreshocks and find that 783 (37.9%) have one or more foreshocks, using our defined space-time window. We observe a decreasing trend of foreshock occurrence with mainshock depth from 0 to 30 km. Also, normal faulting earthquakes have higher foreshock occurrence than reverse faulting earthquakes. We calculate the rates of foreshock occurrence as a function of the magnitudes of the foreshocks and mainshocks, and we do not see a correlation between the sizes of the foreshock and mainshock. For example, for the range foreshocks magnitudes from Mj 1.0 to 3.5, there is about the same probability of occurrence (about 6%) for Mj3, Mj4, or Mj5 mainshocks. Since we have a large number of mainshocks in this study, these results provide good statistics for calculating foreshock-mainshock occurrence.

Effects of Station Distribution and Rupture Directivity on Stress Drop Estimates in the Ridgecrest 2019 Earthquake Sequence

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Earthquake stress drop is an important source parameter related to the average slip on the fault, and hence is widely used in many ground motion and source physics studies. But since it is highly variable and uncertain, the estimates of stress drop and their variability needs to be carefully analyzed before they could be reliably used for prediction of potentially damaging ground motions. In this study we explore azimuthal variation in measured (estimated) corner frequency and resulting stress drop estimates using the recordings from a large number of stations in Southern California. We calculate the stress drop for a number of moderate earthquakes(M3.5-4.5) in the Ridgecrest 2019 sequence using the corner frequencies estimated from a semi-automatic Empirical Green's Function (EGF) Method and a simple circular source model. Simple circular models ignore any rupture directivity or other azimuthal variation. Our initial observations suggest spatial variation in the estimates of stress drops of individual events, possibly due to the effect of station distribution for each. We investigate this by analyzing the azimuthal coverage and any variation in azimuthal estimates of corner frequency for each target and compare these to the spatially averaged stress drop values. We also compare the average stress drop values at different stations for all events to check for consistency or significant bias. This analysis will allow us to explore including the azimuthal distribution of stations as a parameter to characterize the quality of highly variable stress drop estimates and also to carefully relate reliable spatial variation in corner frequencies to the rupture characteristics (i.e., directivity) of events.

Fault Interactions Enhance High-frequency Earthquake Radiation

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The faults on which earthquakes occur sometimes form complex interconnected patterns. The level of this complexity may increase high-frequency ground motions from earthquakes occurring on such faults. We describe ways of quantifying the complexity of groups of faults based on how they are aligned and how densely they are spaced. We find that high-frequency ground motions in Southern California tend to correlate with misaligned faults, suggesting that structural interactions between different parts of the fault system may play a role in generating the ground motions felt during earthquakes. We use simple simulations to understand the physical settings where fault interactions are expected to occur. We suggest that work involving rupture simulations, ground motion modeling and hazards assessments in complex fault geometries should consider the effects of structural interactions.

Insights on Earthquake Source Processes From the 2019 Ridgecrest Earthquake Source Spectra and Its Azimuthal Variation

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The 2019 Ridgecrest, CA earthquake sequence has provided a unique opportunity and a rich dataset to understand earthquake source properties and near-fault structures. Using the high-quality seismic data provided by the SCEC Stress Drop Validation group we first estimate the corner frequency for M2.0-4.5 earthquakes by applying the spectral ratio method based on empirical Green's function (Liu et al., 2020). We relate corner frequency estimates to stress drops assuming the Brune source model and circular cracks. Our preliminary results show increasing stress drops with magnitude for both P and S waves, from 1 MPa for M2.0 events to 10 MPa for M4.0 events, though the limited frequency bandwidth may cause underestimation for small events. The estimated moment magnitude is proportional to the catalog magnitude by a factor of 0.72, which is close to 0.74 estimated by Trugman (2020) for the Ridgecrest earthquake sequence. In the second part of the study, we examine the impact of fault zone structure on the azimuthal variation of the spectra. Using kinematic simulations and observations of the 2003 Big Bear earthquake sequence, Huang et al (2016) showed that fault damage zones can act as an effective wave guide and cause high-frequency wave amplification. We use clusters of M1.5-3 earthquakes in the Ridgecrest region to further examine the azimuthal variation of the stacked spectra and investigate if the near-source structure can affect our corner frequency estimates. We aim to develop robust methods that utilize high-quality seismic data to illuminate earthquake source processes and fault zone properties.

Lab-generated Earthquakes in Heterogeneous Faults With Varying Roughness

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Spontaneous stick-slip motion and associated acoustic emissions (AEs), generated in laboratory frictional sliding experiments, are useful analogues for natural earthquake behaviour. In particular, they have been shown to be an important means of understanding earthquake nucleation and source properties. Previous laboratory studies have shown that stick-slips, AEs and earthquakes are extremely similar: waveforms visually resemble earthquake seismograms with P and S arrivals and codas, while magnitudes for AEs also obey the Gutenberg-Richter relation for earthquakes. Studies such as these are advantageous as heterogeneity in material properties, such as fault roughness, can be carefully controlled and quantified.

We conduct direct shear tests on PMMA (poly methyl methacrylate) at confining pressures ranging from 30-60 MPa to investigate the impact of simulated fault roughness on lab-generated earthquake behaviour. Surface morphologies of roughened PMMA surfaces are quantified using SEM (scanning electron microscope) imaging. Waveforms radiated during slip are measured by piezoelectric crystals on both ends of samples, held within a sample assembly. Following absolute acoustic sensor calibration of the seismic sample assembly (after McLaskey et al., 2015) to remove instrument and path effects from measured waveforms, source properties of lab-generated earthquakes, including seismic moment and stress drop, are derived.

Preliminary results suggest that smoother simulated faults promote instability, with larger stress drops and seismic moments observed. Moreover, the frequency-magnitude distribution of AEs is compared similar examples in the literature. Future work aims to further constrain the relationship between fault roughness and source properties and consider macro-scale implications in fault zones.

Mainshock-aftershocks and Swarm Sequences Highlighted by Fluid-driven Process (Ubaye Region, French Western Alps)

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The Ubaye Region (French Western Alps) is one of the most seismically active regions in France. It is visited by three types of seismic sequence: mainshock-aftershocks sequences (e.g. in 1959, mainshock of ML5.3), swarm sequences (e.g. in 2003-2004 with more than 16,000 events recorded and a maximal magnitude of ML3.4) and mixed sequences (e.g. in 2012-2015 with two mainshocks, ML4.8 in 2012 and ML5.2 in 2014, followed by an abnormally high rate of seismicity). The presence of these sequences highlights the complexity of the processes that drive the seismicity in this area.

To improve our understanding of these processes, we compute 100 new focal mechanisms of aftershocks following the 2014 mainshock and compile a regional catalog of focal mechanisms already published. This catalog shows a surprisingly wide variety of orientations and rupture mechanisms. However, the stress-state orientation obtained from focal mechanism inversion highlights comparable results for different periods and sub-areas: σ1: N24°, plunging 41°; σ2: N201°, plunging 49°; σ3: N293°, sub-horizontal. We then use the inferred stress-state orientation to calculate its amplitude and the fluid-pressure required to activate the fault planes associated to each focal mechanism. We find that most of the events need fluid-overpressure, with 80% triggered by an overpressure lower than 40% of the hydrostatic pressure. Moreover, we observe that even the largest events (e.g mainshocks in 2012-2015 sequence) are supported by fluid-pressure. Therefore, the difference in the seismic crises seems more related to the fluid-pressure evolution (time) than to the fluid-pressure amplitude. For a swarm sequence, the fluid-overpressure remains constant with time, while for a mainshock-aftershocks sequence, it seems to decrease. Therefore, fluid-pressure is likely to be a common triggering of the seismicity in the Ubaye Region, even if the involved processes should differ to explain the different types of seismicity.

Relocation of the 1975 Oroville ML 5.7 Earthquake Sequence and Insights Into Its Origin

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On 1 August 1975, a M_L 5.7 earthquake occurred along the Cleveland Hill fault in the vicinity of Oroville Dam and its reservoir Lake Oroville in northern California. The event occurred soon after refilling of the reservoir from the largest summer drawdown recorded up to that time. Because of the proximity of the 1975 sequence and its timing relative to refilling, it was immediately suggested that the earthquakes were triggered by the reservoir. Soon after the mainshock, seismic stations were deployed by several organizations to record and locate the aftershocks. The aftershocks defined a 15-km long, 60 degree-dipping normal fault with events located to a depth of 10 km. To gain greater insight into the rupture process and geometry of the Cleveland Hill fault and the cause of the earthquakes, a double-difference relocation of the sequence was performed. A velocity model for the area was developed using the program VELEST. About 1000 well-recorded events from July 1975 to June 2018 were relocated using the updated velocity model and the program HypoDD. The relocated sequence shows similar trends to previous locations, but with tighter clustering in map and cross-section views. Seismicity aligns along a plane dipping approximately 55 to 60 degrees west, with seismicity extending to a depth of 14 km. Although the majority of events are located several kilometers south-southwest of the reservoir, the northern extent of the aftershock zone reaches the southern edge of Lake Oroville. The relatively shallow nature of the foreshock and possibly mainshock, assuming they were co-located, might suggest that the sequence was initiated in an area influenced by pore pressure increases due to Lake Oroville. There does not appear to be any clear spatial migration of seismicity after the mainshock. Although there were no earthquakes located near Lake Oroville in the years prior to 1975, the area appears to have been reactivated with events occurring up to present.

Scattering of Moment Tensors During Aftershock Sequences at Global and Local Scales

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Observations of regional stress field rotations in the wake of large earthquakes have been used to argue for a weak seismogenic crust. Identifying these stress rotations requires high-quality foreshock and aftershock source mechanisms, which has largely restricted robust observations to large earthquakes along subduction zones or strike-slip plate boundaries. Whether coseismic stress rotations are general features of seismicity, or are limited to a handful of well-studied events in specific tectonic environments, is an open question. If stress rotations are ubiquitous, they could serve as useful data to study crustal strength and discriminate between models of coseismic stress rotations.

To evaluate the generality of coseismic stress rotations, we compare foreshock and aftershock moment tensors to those of mainshocks using two earthquake catalogs. We use a nearest-neighbor clustering algorithm to identify earthquake sequences in the global ISC-GEM catalog and the regional Southern California catalog. Using an inner-product-based pairwise measure of moment tensor similarity, we demonstrate that, in both catalogs, aftershocks are less similar to their respective mainshocks than foreshocks are. We show that this effect, which we call moment tensor scattering, is generally observable for earthquakes as small as M 3.0. We further demonstrate that mainshock-aftershock similarity is lowest immediately following a mainshock and find evidence that mainshock-aftershock similarity recovers logarithmically to pre-mainshock levels on decadal timescales. We conclude that moment tensor scattering is a generally observable feature of seismic sequences which may be useful in future work to discriminate between models of crustal strength.

Seismic Magnitude Clustering Is Prevalent in Laboratory and Field Catalogs

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Although spatial and temporal clustering of earthquakes is well established, magnitude clustering is a matter of active debate. If magnitude clustering does exist, it has practical applications in earthquake forecasting (current ETAS models do not include it) and improved understanding of seismogenesis. We investigated whether magnitude correlations between sequential events exist in a variety of field and laboratory studies. The field study was a statistical analysis of both natural and induced earthquake catalogs, while the laboratory study examined fracture processes in a variety of different loading protocols, stress conditions and rock types. Filters based on the magnitude of completeness and interevent times were applied to address previous study concerns of network detection limitations and short-term aftershock incompleteness. In both field and laboratory analyses, we observed significant magnitude clustering on the order of 1-2% more than would be expected in a random distribution. This phenomenon was still observed after various filters were applied, demonstrating that magnitude clustering is not an artifact but a widespread phenomenon. We observed magnitude clustering at a wide range of spatial scales, from millimeters to meters to kilometers. The laboratory results identified magnitude clustering is independent of loading protocol or rock types, but it is controlled by geometric constraints (i.e., fault boundaries) and a shear stress condition. The field results also demonstrated magnitude clustering is not restricted to a particular fault type. Both the lab and field analyses found magnitude clustering is most prominent at short time scales, suggesting this is part of the physical process. Possible hypotheses include: fault patch rupture with incomplete strain release promotes similar re-rupture soon after, or conditions controlling event size change slowly enough that events with short time separation are more likely to have similar magnitudes.

The Southern Alps Long Skinny Array (SALSA): Virtual Earthquake Analysis of the Alpine Fault Between Milford Sound and Maruia

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The Alpine Fault provides an exemplary focus for earthquake science. It produces large (magnitude~8) earthquakes remarkably consistently that pose substantial seismic risk to population centres and infrastructure in central and southern New Zealand. Earthquakes occur on the central and southern portions of the Alpine Fault at intervals of 263±68 yr and 291±23 yr respectively; more than 300 years have elapsed since the most recent big earthquake in 1717 CE. A fundamental challenge is to determine how parts of the fault are accumulating stress and how much the ground will shake across New Zealand given the resulting patterns of slip during an eventual earthquake. To address this, we must accurately and efficiently compute the ground motions produced by a broad range of plausible but as yet unobserved rupture scenarios.

The Southern Alps Long Skinny Array (SALSA) is being deployed for 18 months to explore how the Alpine Fault's structure, heterogeneity and present-day state will affect earthquake slip and ground-shaking in future large earthquakes. The main phase of SALSA's construction was completed in November 2021 with the installation of 25 broadband sensors; an additional seven sensors are scheduled for installation in early 2022. Once fully deployed, SALSA will consist of more than 40 temporary and permanent broadband sensors spaced 10–12 km apart along a ~450 km length of the Alpine Fault between Milford Sound and Maruia and augmented by 16 short-period sensors.

As well as characterizing local seismic sources such as microearthquakes and V/LFEs, SALSA will be used to synthesise Green's functions representing the farfield response to incremental slip anywhere on the fault surface. By combining these Green's functions with rupture models based on recent findings regarding along-strike fault structure, fault rock rheology and rupture segmentation, we will compute the ground motions at locations of interest throughout New Zealand produced by large numbers (millions) of complex, geologically-informed and plausible rupture scenarios—"virtual earthquakes"—which would otherwise be computationally intractable.

Toward a Self-consistent Mw Catalog for the Central Walker Lane Fault System

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The Walker Lane Fault system is one of the most seismically active regions in the western U.S., and recently this region experienced several moderate earthquakes (M >= 5) including the 2020 M 6.5 Monte Cristo Range, 2020 M 5.2 Mono Lake, and the 2021 M 6.0 Antelope Valley sequences. A key to better understanding the tectonic stress is systematically evaluating the seismic moment and energy release of individual earthquakes. To develop a self-consistent moment magnitude (Mw) catalog for the Central Walker Lane seismicity, we used the coda magnitude method proposed developed by Mayeda & Walter (1996) and Mayeda et al., (2003) that provides a consistent measure of Mw over a broad range of event size using stable, coda-derived moment-rate source spectra. A total of 39 selected earthquakes (3.5 <= M <= 6.0) was used to calibrate station and path effects, coupled with independent ground-truth source spectra that were used to break the path and site effect trade-offs. We analyzed over 3000 envelope waveforms (11 narrow bands ranging between 0.05 and 10.0-Hz) collected at 19 broadband stations located in and around our target area. Our preliminary results find excellent agreement with waveform modeled moment tensors which will allow for stable estimates of Mw, well below what can be routinely and accurately waveform modeled. Furthermore, preliminary results suggest some of the Antelope Valley earthquakes are characterized by higher-stress drop than other western U.S. earthquakes. Additionally, events within the Sierra Nevada block also show higher stress, which is consistent with observed negative residuals of Mw-ML relative to other events in northern California.

Velocity Structure and Deep Earthquakes Beneath the Kinnaur, NW Himalaya: Constraints From Relocated Seismicity and Moment Tensor Analysis

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The optimum 1D velocity model is calculated for the Kinnaur sector of the NW Himalaya utilizing the arrival time information of the local earthquakes (137 no.) recorded with 12 broadband seismic networks within the azimuthal gap of ≤ 180°. This optimum 1D velocity model is a five-layer model and ranges from the surface to 90 km in the shallow mantle. P velocity varies from 5.5 km/s to 8.6 km/s in the crust and upper mantle and S-wave velocity varies between 3.2 km/s to 4.9 km/s for the same range. When we relocated the earthquakes with the Joint Hypocenter Determination program incorporating the optimum 1D velocity model, it resulted in a lower RMS residual error of 0.23s for the hypocenter locations compared to initial hypo71 locations. A total of 1274 P and 1272 S arrival times were utilized to compute station delays. We observed positive variations in P-station delays from -0.19s below the PULG station to 0.11s below the SRHN station. Similarly, for S-station delays, we observed negative delays at each individual site from -0.65s at LOSR station to -0.16s at SRHN station. This large variation in P and S-station delays corresponds to the 3-D nature of the sub-surface below the Kinnaur Himalaya. The relocated seismicity is clustered along the STD fault at sub-Moho and Moho depths ranging between 40 km to 80 km. We also observed bimodal depth distribution of seismicity in the Higher and Tethys Himalayas. The occurrence of earthquakes down to a depth of ~0-40 km and 50-80 km in the study area can be interpreted in terms of stress contribution from inter-seismic stress loading associated with the India-Eurasia collision tectonics. The computed focal mechanisms exhibit generally the flexing of the Indian plate below the Lesser Himalaya with shear parallel to the strike of the MCT

and extension orthogonal to it. Thus we can consider the crust and the shallow upper mantle down to depths of 120 km to be seismogenic in nature and is capable of producing the microseismicity beneath the Kinnaur Himalaya.

Earthquakes in the Urban Environment

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Fabian Bonilla, Université Gustave Eiffel (luis-fabian.bonilla-hidalgo@univ-eiffel.fr); Philippe Guéguen, ISTerre, Université Grenoble Alpes (philippe.gueguen@univ-grenoble-alpes.fr); Stefano Parolai, Istituto Nazionale de Oceanografia e de Geofisica Sperimentale (sparolai@inogs.it); Thomas Pratt, U.S. Geological Survey (tpratt@usgs.gov); Chiara Smerzini, Politecnico di Milano (chiara.smerzini@polimi.it)

Assessment of Earthquake Hazard and Risk for Tofino, British Columbia

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Tofino is a hub of shared services for more than 4500 residents of West Coast communities living within the Clayoquot Sound Biosphere Region, on Vancouver Island, British Columbia. Annual visitors estimated at 5000-8000 daily during peak summer months contribute to a strong tourism economy in the area. A probabilistic earthquake hazard and risk assessment is conducted for Tofino and neighboring communities. It aims to provide guidance on disaster risk reduction planning at a local scale. The 6th generation seismic hazard model of Canada is adopted as a regional base model. It is verified/refined to accurately represent the seismicity potential and resulting ground motions in the study area. An exposure database of buildings and population is developed for the risk assessment. Appropriate fragility and vulnerability models are combined with seismic hazard estimates to determine the associated potential damage and loss.

The findings of the study will inform mitigation efforts with the improvement of seismic resiliency in Tofino and neighboring communities, including the design and assessment of tsunami vertical evacuation structures, development of evacuation routes, planning of infrastructure siting and emergency response planning. Additionally, the results will provide guidance on seismic monitoring for early warning and emergency response, in order to maximize the disaster risk reduction efforts.

Recorded Earthquake Response of the New Self Anchored Suspension (SAS) Bridge of the San Francisco Bay Bridge System–A Preliminary Study

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I analyze the seismic behavior and performance of the Self Anchored Suspension (SAS) Bridge of the San Francisco Bay Bridge System, by considering response data recorded during the October 14, 2019 Mw4.6 Pleasant Hill earthquake (www.stronmotioncenter.org). The new SAS bridge went into service within the last decade as a replacement for the older truss bridge that spanned between Yerba Buena Island and East Bay. During the October 19, 1989 M6.9 Loma Prieta earthquake that occurred ~100 km away from the Bay Bridge, a section of the upper deck of the old truss bridge had fallen onto the lower deck—thus closing this important lifeline between San Francisco and East Bay. The new SAS bridge part (as well as the rest of Bay Bridge) is instrumented by the California Strong Motion Instrumentation Program of the California Geological Survey in collaboration with the California Department of Transportation. Only one set of response data acquired during the referenced 2019 small magnitude event that generated low amplitude shaking of SAS is studied herein—having close to approximately 90% of a total of 85 channels (for SAS part) recorded.

The replacement SAS is unique and, as the name indicates, is self-anchored and suspended by a single tower that is pivotal in trafficking the cable and hanger system to support the eastbound (E) and westbound (W) decks. At each of the west and east end of SAS, there is a hinge system that ties the W and E decks to the skyways.

The data analyses highlight the complex and yet identifiable coupled response of the deck, tower and cable system. Both acceleration and displacement time-history data are used to extract significant frequencies using system identification methods including spectral analyses. Results are compared to those from finite element model analyses carried out during design and analysis process of the bridge in the early 2000's (Nader, Lopez-Jara and Mibelli, 2002). Differences are discussed in terms of the low-amplitude shaking caused by the particular seismic event.

Ground Motion Spatial Variability Due to Combined Effects of Site and City Responses in a Sedimentary Basin

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Developed within the framework of the Ritmica project supported by the IDEX JEDI of the University Côte d'Azur, the objective of this work is to assess the respective impact of the site stratigraphy, of the geology and of the building on the seismic hazard. To do this, one of the highest seismic risk areas in France mainland is chosen as study case: the lower Var valley. Many experiments have been carried out there for several years, including instrumentation of buildings, engineering structures and free-field sites which have made it possible to define and describe the geological configuration of the valley and the dynamic behavior of some of the surrounding structures.

We first revise the 3D geotechnical model of the valley from available geotechnical and geophysical data and second calibrate simplified numerical model of building in order to establish a 3D finite element model of the valley including buildings on the top. This model is used to numerically simulate the seismic wave propagation in the Var valley using a synthetic earthquake. A numerical study done on five finite element models of building (4 low-rise and one high-rise, reinforced concrete and masonry) shows that bending type buildings are the most prone to SSI and that stiffness horizontal irregularities play an important role in SSI. A dense instrumentation campaign on several buildings in the valley allows to check that their first mode shape, used in the calibration of simplified model, corresponds to a bending mode. The analysis of the rocking spectral ratio and of random decrement functions is useful for the characterization of SSI from vertical temporal series at the base of buildings. Thanks to the numerical simulation of the seismic wave propagation in the 3D site-city model, the impact of the 3D site response and the presence of buildings on the variability of the ground motion through the valley is analyzed through a parametric study.

Testing Machine Learning Models for Regional Scale Building Damage Prediction

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Earthquakes may not occur frequently; however, they contribute significantly to the physical and social consequences of natural hazards. Information regarding the extent and spatial distribution of potential seismic damage within a built environment is crucial for decision-makers, emergency planners, insurers, and re-insurers. On urban or regional scales, seismic damage assessment remains relatively difficult owing to a significant amount of time and resources required to acquire information and conduct a building-by-building seismic damage assessment. However, the application of novel methods based on machine learning has opened a new perspective for urban seismic damage assessment. Yet, its effectiveness and the relevance of the results yielded with respect to the objectives need to be further improved. The main objective of this study is to investigate the effectiveness and relevance of machine-learning models for predicting spatially-distributed seismic damage at the urban/regional scale using a large portfolio of buildings.

For this study, we considered the key structural parameters of a portfolio of buildings and the post-earthquake damage surveyed after the Nepal 2015 earthquake, combined with macro-seismic intensity values provided by the United States Geological Survey ShakeMap tool.

Among the methods considered, the random forest regression model provides the best damage predictions for specified ground-motion intensity values and structural parameters. For traffic-light-based damage classification (three classes: green, yellow, and red-tagged buildings based on post-earthquake damage grade), a mean accuracy of 0.64 is obtained by restricting the learning to the basic parameters of buildings (i.e., number of stories, height, plinth area, and age).

This study confirms the effectiveness of machine learning methods for earthquake scenarios or immediate damage assessment once ground-motion information is published via operational tools, such as the USGS ShakeMap. While still preliminary, the result obtained from such models may assist stakeholders and decision-makers for earthquake disaster risk mitigation.

High-resolution Amplification Model for an Urban Area Using the Weak Motion From Earthquakes and Ambient Vibration Data

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Weak ground-motion earthquake observations can be used to derive empirical amplification at soil sites (e.g. by using Standard Spectral Ratio—SSR). However, in densely populated urban areas, especially located in low-to-moderate seismicity zones, the seismic monitoring network has to operate sometimes for several years to record a statistically sufficient number of events due to the high level of background noise. Long recording time and lack of free-field space in the city limits the possibility of using empirical methods based on earthquake observations to map the site response with a high spatial resolution. Therefore, we tested the hybrid SSR approach (SSRh) that allows assessing the variability of site response in the sedimentary basin using mainly ambient vibration data supplemented by a few sites having amplification functions derived from recorded earthquake ground motion. The study area is the city of Lucerne (Switzerland) which is located on soft soil deposits. The seismic hazard is moderate, with evidence of several strong historical earthquakes (i.e. Mw5.9 in 1601) which caused damage in the city. By combining ambient vibration that we recorded at 100 sites with earthquake recordings from a temporary network installed for about one year, we developed a high-resolution local amplification model for the area. The resulting amplification factors are higher than 10 at about 1Hz in some parts of the city. The comparison of the amplification functions derived using earthquake-based and hybrid approaches at selected sites show good agreement. In addition, we observe consistency with geological data and site response proxies such as the fundamental resonance frequency. However, the uncertainty of the method remains high due to the daily variability of ambient vibration and the results are influenced by the position of the stations of the temporary network. This study is part of the URBASIS-EU project in the framework of the Horizon 2020 ITN.

Urban Seismology: Installing a BASIN Seismic Array in Yangon, Myanmar During COVID-19

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Based on experience from the 744-station BASIN (Basin Amplification Seismic Investigation) experiment that was carried out by volunteers in 2017-2019 in the greater Los Angeles area to help improve ground motion estimates from a large earthquake on the San Andreas fault, a large seismic installation was planned in early 2020 in Yangon, Myanmar. This project would involve the in-person training of participants from 19 universities around Myanmar. Yangon, one of the fastest growing cities in Myanmar has a population of over seven million and is located in close proximity to the Sagaing fault, a major fault in Southeast Asia that has historically produced magnitude >7 earthquakes. Accurate estimates of the ground motions that may occur in this region during a large earthquake rupture are critical and can lead to better city planning and management to help prevent the loss of life and property. This requires an understanding of the subsurface and geologic structures that underlie the city and presents an opportunity for capacity building in geophysics in Myanmar. Due to COVID-19 restrictions, fieldwork for the Myanmar Universities Seismic Experiment (MUSE) was modified and included 11 professors and students in Yangon who were remotely trained on the installation of nodal seismic stations.

The installation began in March 2020 and took 2.5 days with 3-4 teams. We have recorded data at 110 three-component nodes from the IRIS PASSCAL instrument center (X1 network) that were installed along three seismic profiles with a station-spacing of ~300 m in one of the first US-based international efforts of this kind. Most instruments were hosted by homeowners. Myanmar went into a lockdown and retrieval of the nodes occurred in June 2020. Despite severe monsoon flooding, no nodes were lost or damaged. We will present best practices in fieldwork and international collaborations and how this project benefitted from lessons learned during the Los Angeles area BASIN experiment.

Continuous Seismic Monitoring of a Building Over 20 Years

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Since 2001, the Southern California Seismic Network has archived continuous waveform data from strong motion station CI.MIK in Caltech Hall (formerly called the Robert A. Millikan Memorial Library), a nine-story reinforced concrete building. A simple spectral analysis of this 20-year record reveals that the fundamental frequencies of the building have increased gradually and monotonically by 5.1% (E-W) and 2.3% (N-S), corresponding to ~10% (E-W) and ~5% (N-S) increases in stiffness. This finding is unexpected, as previous analysis of forced vibration tests and earthquake strong motion records has shown that between 1968 and 2003 the fundamental frequencies decreased by 22% (E-W) and 12% (N-S). The historical softening of Caltech Hall has been attributed to minor structural damage and changes to the soil-structure system during the 1971 M6.6 San Fernando, 1987 M6.1 Whittier Narrows, 1991 M5.8 Sierra Madre and 1994 M6.7 Northridge earthquakes. Today, the building's apparent structural stiffness is comparable to what it was in 1986, before the Whittier Narrows earthquake. While some of the incremental changes in frequency may have been caused by interior renovations to the building, in particular a reduction in mass during its conversion from a library into an office space around 2003, the quasi-linear healing trend over the past two decades is largely a mystery. In this presentation we examine the 20-year record of ambient and forced vibrations in detail and discuss competing evidence that the healing trend is either due to changes in soil-structure interaction or the integrity of the structure itself. We also look at the response of Caltech Hall to earthquake loading for over 300 events, highlighting the building's dynamic non-linear response to strong motion.

A New Approach for Soil-structure Interaction Assessment and Its Application to the Matera Experiment

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Soil-structure interaction (SSI) is the process in which the response of the soil influences the motion of the structure and conversely. For a better understanding of this phenomenon, we propose an approach aiming at the evaluation of the different components of the wavefield in the surroundings of a

structure. The approach is based on the analysis of earthquake recordings of sensors installed both in the surroundings and in the structure itself. First, the structure's dynamic behavior is studied. In particular, its resonance frequencies are identified in order to define the frequency band of interest. Second, a joint deconvolution of the recordings of the sensors installed both in the building and in the free field is performed to highlight the interaction between soil and structure. The last step of our approach is a polarization analysis of the deconvolved wavefield to classify the detected signal. The novelty of the presented approach is the combination of the joint deconvolution and the polarization analysis in SSI assessment.

We applied the proposed approach to earthquake recordings from the SSI experiment in Matera, Italy. Additionally, we introduced an analytical model for the identification of the deconvolution phases related to the propagation of the waves radiated from the building. Our preliminary results of the analyzed three-component wavefield recorded on the nearby athletic field show that, for the studied test site, we can identify signals with relatively high energy content at frequencies matching the building resonance frequencies. The analysis of the elliptical parameters indicates that the signals, which might originate from the building itself, have mostly linear polarization.

Numerical Coupling Of 3D Physics-based Ground Motion Simulation With Structural Response

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Physics-Based Simulations (PBS) are becoming a more and more appealing tool to provide realistic predictions of earthquake ground motion at regional scale, taking into account site-specific geophysical attributes. In an urban environment, densely located buildings can further modify the wave propagation owing to the so-called site-city interaction (SCI) effects. Modelling of such effects requires addressing a multi-scale seismic phenomena including, in a single model, the seismic source, the propagation in 3D heterogeneous materials, and the dynamic response of civil engineering structures. Because of the computational burden of these multi-scale models, the practicality of such applications is limited, but it is expected to attract further attention for developing advanced "source-to-structure" seismic analyses.

To overcome this knowledge gap, a new module is being developed inside the high-performance spectral element code SPEED (http://speed.mox.polimi.it/) to couple regional ground motion simulations with simplified models for non-linear structural response. On top of the geophysical domain, the buildings are modelled as non-linear Single- or Multi-Degree of Freedom systems (SDOF and MDOF). This approach does not require complex preprocessing and additional computational resources while running 3D PBS. In this work, we aim at presenting a set of verification and validation tests of the new SPEED module. For the validation test, we consider the CAMUS-4 experiment consisting of a 5-story RC building supported on top of a sand layer. This building is modelled as a (i) bi-linear SDOF system and a (ii) MDOF system with a nonlinear flexural-shear model, and the resulting structural response from the coupled PBS is compared against the experimental data. The numerical tests presented in this contribution represent the seminal steps for developing more complex case studies to shed light on the relevance of SCI effects in seismic wave propagation in urbanized environments.

Seismic Soil-structure Interaction Analysis of Multi-story RC Building Subjected to Different Earthquake Ground Motions Considering Various Soil Types

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In this paper, the seismic responses of a reinforced concrete structure under different earthquake ground motions and soil conditions considering soil-structure interaction (SSI) are investigated. For this purpose, the dynamic analysis was carried out for a multi-story reinforced concrete building which is founded on three different types of soils, and two different types of foundation, with and without soil interaction. In this study, the local soil conditions and the characteristics of input motions are important parameters for numerical simulation and seismic analysis. The analysis was performed for two different cases: fixed base without considering SSI and flexible base by considering SSI. Considering the soil property of the building site, analysis was done for three types of soil which are defined as soft, medium and rock. Two types of earthquakes including Kobe and Kocaeli earthquakes were used as input motions in the seismic analysis. A 2D finite element model of the soil-structure system was established with Mohr-Coulomb failure criterion under plane-strain conditions. Dynamic analysis of the proposed structure-soil coupled model was performed in the time domain using Plaxis 2D, a commercial FEM software. According to the result of the dynamic analysis, the dynamic responses of the structure including forces, displacements and accelerations are calculated and shown in graphic forms. The analysis which is obtained by the Kobe earthquake is compared with the results obtained by the Kocaeli earthquake for different soil conditions. For instance, the numerical analysis demonstrated that the displacements values are increasing from hard rock to soft soil. In addition, it is seen that the displacement values are different for each kind of earthquake ground motion, meaning that the structure and soil have different responses to various kinds of earthquake ground motions. Results show that the phenomenon of structural soil interaction must consider in the building seismic analysis. Furthermore, more conclusions were carried out according to the obtained results and important findings are outlined.

Earthquakes in the Urban Environment

Poster Session · Friday 22 April ·Conveners: Fabian Bonilla, Université Gustave Eiffel (luis-fabian.bonilla-hidalgo@univ-eiffel.fr); Philippe Guéguen, ISTerre, Université Grenoble Alpes (philippe.gueguen@univ-grenoble-alpes.fr); Stefano Parolai, Istituto Nazionale de Oceanografia e de Geofisica Sperimentale (sparolai@inogs.it); Thomas Pratt, U.S. Geological Survey (tpratt@usgs.gov); Chiara Smerzini, Politecnico di Milano (chiara.smerzini@polimi.it)

Development of the Korean Peninsula VS30 Map Based on Terrain Classification Derived from DEM

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The national seismic intensity service in South Korea provided by Korea Meteorological Administration (KMA) has used the ShakeMap (Wald et al., 2006) that uses V_{S30} as a main site variable characterizing the site amplification (KMA, 2018). The V_{S30} is estimated from geophysical exploration. However, it is practically impossible to conduct geophysical exploration at the entire area of the Korean Peninsula. Therefore, the KMA has used the V_{S30} map (Choi et al., 2022) developed using proxies such as slope gradient and geologic layers for the input site variable in the ShakeMap.

In addition to the geologic based V_{S30} map, this study suggests a new V_{S30} map using topographic parameters such as slope gradient, surface texture and local convexity. Surface texture is a measure of spatial intricacy representing a change in sign of slope aspect or curvature per unit area. Local convexity is introduced to distinguish low-relief features such as alluvial fans. In previous studies, the land was classified into 16 terrain classes using these three variables (Iwahashi and Pike, 2007) and terrain-class-based V_{S30} schemes were suggested (Yong et al., 2012). Per Iwahashi and Pike (2007), classifying terrain depends on the target region. Each class is defined by dividing the range of slope gradient, surface texture or local convexity by half. Therefore, there are different criteria based on the target region and resolution, and Iwahashi and Pike (2007) suggest different criteria for World, Japan and Shimukappu regions. This study targets the Korean Peninsula. A terrain classification map according to the Iwahashi and Pike (2007) method is created, and the optimal V_{S30} for each terrain class is suggested using 11,260 estimated V_{S30}s in the Korean Peninsula. This new V_{S30} map that is not based on the geologic map can be used to reduce the uncertainty of V_{S30} prediction by combining with the geologic-based V_{S30} map.

Exploring Sources Uncertainties in Building Response Prediction Using Real Earthquake Data

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Performance-based earthquake engineering is a probabilistic decision-making framework aimed to mitigate seismic risk, based on a comprehensive scientific foundation. In this framework, the structural response and the associated uncertainties are conditioned by time-history seismic excitation, considering the ground motion intensity measures (IM) at which the structural response value (EDP) is exceeded. Often, numerical methods are used to model the EDP for given IM (EDP|IM), thus, uncertainty is inevitable.

The experimental data from the full-scale observations are much more representative of the complex physical process than even the most sophisticated laboratory or numerical experiments, integrating them into our modes helps to identify the sources of epistemic uncertainty.

The main objective of this study is to quantify the sources of uncertainties in building response prediction using real earthquake data recorded at the top and the bottom floors of buildings. We explored the region-to-region, building-to-building and within-building uncertainties associated with earthquake magnitude-distance and aging.

We observed that the velocity-related IMs result lowest variability for predicting EDP|IM. The regional distinction does not bring any significant gain in total uncertainty (4% on average), however, distinction by type of construction and specific building contributes respectively 22% and 38% to the total uncertainty. Concerning the IMs that make EDP conditionally independent from the magnitude and source-to-site distance and the actual health of the structure contributes significantly to the total uncertainty (51% and 55% respectively).

Significant improvement in seismic risk decision-making will be achieved by appropriately handling the above-identified sources of uncertainties. International collaborative efforts should be strengthened to collect and share more data from structures to enhance understanding of the real physical process involved in the structures.

Regionally Adjusted Empirical Ground-motion Models: Application to Greece

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Ground Motion Models (GMMs) are typically developed from ground motion waveforms from numerous earthquakes, recorded at multiple stations in different regions. This ensures that the developed GMMs are robust and reliable across the required magnitude-distance range. However, for Probabilistic Seismic Hazard Analysis, there is an increasing demand for local or regional ground-motion models. Such local models cannot be robustly defined in data-poor regions. The aim of this work is to therefore calibrate or regionally adjust existing GMMs, derived from a compendium of data, and generate a suite of models for the target region while accounting for epistemic uncertainty. This is achieved through an optimisation-based calibration technique utilizing the concept of stochastic area metric. The European Engineering Strong Motion (ESM) dataset is used in this study. We adapt the tectonic regionalization to develop a more consistent and meaningful regionally adjusted GMM. The procedure is applied to one of the most commonly used European GMMs—Bindi et al. (2014, B14). We were able to define a Greece-specific GMM, reducing the associated area metric value of B14 by 30%. An alternative way to derive models in sparse data regions is to utilise stochastic modelling to simulate ground motion data. We have therefore analysed and updated the seismological parameters of an existing regional stochastic model using SMSIM, executing a similar optimisation algorithm to develop a locally adjusted stochastic model. This framework for the calibration and updating of models can help achieve robust and transparent regionally adjusted GMMs.

The Seismic Fingerprint of Large Vehicles in an Industrial Facility

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Large vehicles are used in industrial settings to perform operations involving the movement of material or equipment. Such vehicles can produce mechanical energy that propagates at short distances as seismic signals, either as the result of sound emanating from the vehicle engine or by the generation of surface waves due to the interactions between the ground and vehicles. We used a network of seismic sensors deployed along the roads of an industrial complex to analyze the signals and patterns generated by large facility vehicles following routine paths related to operational events. Data from a GPS datalogger mounted on the vehicles (two tractors and a pick-up car) were used as ground truth. We analyzed the signals at station and network levels. At station level, the seismic signals from approaching vehicles display clear pulses with broadband energy that can last multiple seconds depending on the speed of the vehicle and geometry and surface conditions of the road. We applied an anomaly detection algorithm to identify such pulses in the continuous data and combined that with frequency dependent polarization analysis to estimate vehicle travel direction. We found that large vehicles (tractors) generate polarized signals, while the signals from small vehicles do not have a high level of polarization. At network level, the slow speed of vehicles inside the complex and the spatial distribution of sensors allow estimating vehicles' routes by tracking the movement of energy pulses in network. Our results show that seismic measurement can provide us a low-profile tool to characterize some features of the movement of large vehicles and identify patterns in the seismic wavefield that are signatures of the movement of vehicles involving operational events.

The Effects of Sedimentary Basins on Earthquake Ground Motions

Oral Session · Wednesday 20 April and Thursday 21 April · 8:00 AM Pacific

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Blind Prediction of 3D Seismic Site Response in Near Field Extended Fault Scenarios: Application to the Nuclear Site of Cadarache, France

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Physics-Based numerical Simulation (PBS) is widely employed to predict several realizations of a future earthquake scenario. Earthquake simulators are as powerful as sensitive to large natural uncertainties on the underlying geological and seismological models, especially when focusing on regional ground shaking simulations including active faults, basin-like geology and surface topography. In this study, the power of high-fidelity PBS is employed to understand and predict the near-field seismic response of the experimental nuclear site of Cadarache, located nearby the active Middle Durance fault, in South-Eastern France. The models implement a regional geological model interpreted from in situ experimental campaigns. Broad-band (0-10 Hz) synthetic ground motion prediction is rendered for different finite-fault near-field scenarios, comparing peak ground motion with adapted Ground Motion Models (GMM) and shedding light on complex basin-like 3-D site effects that may occur nearby the Cadarache nuclear facility.

The PBS capture the spatial distribution of 3-D site effects, differing from the GMM estimation which simply discerns between rock and alluvium sites based on the Vs30 estimation. Within the Cadarache sedimentary basin, we find most of relevant factor to determine the predicted intensity are due to the impedance contrast and the shape of the basin. A stronger amplification is obtained at high frequencies across the transverse direction, whereas lower amplification is observed along the longitudinal direction.

From Trough to Basin, Regional Ground Motions and Local Amplifications in Israel—Insights From Numerical Modeling

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The Dead Sea Transform (DST) is an active tectonic boundary dominating the seismicity of the Eastern Mediterranean. A slow slip rate, < 5 mm/y, results in a relatively low seismicity. The Israel seismic catalog (1983-present) includes more than 23,000 events, but only 15 are M > 5 and no M > 6 event was ever recorded. Israel's pre-instrumental catalog spans over 3000 years and includes up to fourteen M > 7 events in the past two millennia.

The 105 km of strike-slip motion along the DST forms a series of deep and narrow pull-apart basins, with depth similar to their width, reaching >10 km in the Dead Sea area. The sedimentary filling of the basins consists mainly of post-Miocene, low-density (<2100 kg/m^3) and low-velocity (V_S < 1200 m/s) sediments, bounded by stiff walls (V_S > 2000 m/s), resulting in a sharp impedance contrast between the basin fill and surrounding rocks.

The geological structure of Israel exhibits considerable spatial heterogeneity over short scales: deep pull-apart basins along the active DST faults, and the Zevulun, Harod and Jezreel Valleys along the Carmel fault zone (CFZ, a northwest splay of the DST). The vulnerability of Zevulun Valley, underlain be a deep sedimentary basin, is particularly crucial because of dense population and high concentration of industrial infrastructure. The Israeli coastal plain, a densely populated region (on average 9000 people per km^2), is underlain by a westward thickening sedimentary wedge (SW).

We study the effects of DST on regional ground motions using 3-D numerical modeling. We show that ground motions and ground motion amplifications atop the sedimentary structures (e.g. the Zevulun Valley) are products of the complex interactions between the inter-basin sources of the DST trough and the sedimentary structures along the CFZ and the SW. Based on the numerical modeling, we developed ground motions attenuation model (AM) for M 6 and M 7 earthquakes in Israel. The proposed AM bridges the M > 6 data gap of the Israel seismic catalog and provides valuable input for mitigation of imminent seismic hazard.

S-wave Site Amplification Factors of KiK-net Borehole Stations Obtained by Generalized Spectral Inversion

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We report the results of the separation analysis of strong-motion spectra, which we have been conducting for several years, focusing on the underground observation records of KiK-net by the National Research Institute for Earth Science and Disaster Resilience. We calculated the spectral site amplification factors (SAFs) at KiK-net sites for both surface and borehole records. The observed SAFs are obtained by the generalized spectral inversion technique for a short (5 to 15 s) duration of S-wave relative to the same reference spectra observed as the hypothesized outcrop motions on the seismological bedrock (Nakano et al., BSSA, 2015). The results show that non-negligible amplification is observed even in the low-frequency range below the fundamental peak frequency in both surface and borehole records due to the common velocity structure below the borehole sensors, that interference between incident and reflected waves is clearly observed as troughs only in the spectra of borehole records and that both real soil amplification and interference between incident and reflected waves contribute to the surface-to-borehole spectral ratios (SBRs). We should note that the SBRs are not the same as SAFs on the surface even if the borehole sensors are embedded deeply into the hard rock. This is so because there should be site amplifications by the layers below the borehole sensors and fictitious amplifications by the interference between incident and reflected waves. Although these facts are theoretically obvious, it is significant that we confirmed here the levels of amplification by two different effects as observational facts. These facts are difficult to obtain unless we use the outcrop of the seismological bedrock motions as the reference of SAFs and we focus on the S-wave portion of the seismograms. For the 3D basin effects, we can use the spectral ratio between the whole duration and S-wave portion (WSR) as a correction factor as proposed by Kawase et al. (ESG6, 2021).

Surface Waves in Mexico City From the Pacific Coast Subduction Earthquakes

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Since the 80's, the subduction earthquakes that occur on the Mexican Pacific coast, with shallow depths, have been recorded by a significant number of accelerometric stations in Mexico City, such as the Michoacán earthquake M8.1 of September 19, 1985 and the recent Guerrero earthquake M7.1 of September 7, 2021, which was recorded by the currently networks deployed in the city. According to their magnitudes, these events have caused from minor damages to widespread structural collapses. The recordings of vertical motion of the Valley of Mexico show clear Rayleigh surface wave trains, that have similar characteristics like periods, amplitudes and durations, among stations and are recurrent. These conspicuous properties appear to be very stable in space and time, showing little influence of site effects. Unlike the vertical direction, the ground motion in the two horizontal directions is strongly affected by the geological properties of the Valley. Essentially the trapping of energy at the uppermost soft layers is responsible of site effects.

In this work, five subduction earthquakes that occurred along the Mexican Pacific coast, from Michoacán to Ometepec, are analyzed using the records of three accelerometric networks deployed in Mexico City. The directivity of surface waves in the Valley of Mexico and the focal mechanisms of these events are analyzed. The local generation of surface waves is studied using a kinematic analysis in the frequency-wave number domain (*f*-k) and several spectral techniques in frequency-time domain. These results allow to draw a preliminary explanation of the behavior of the Valley for this type of earthquakes.

Seismo-VLAB: A Finite Element Simulation Platform for Basin-scale 3D Site Response Analyses

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Physics-based ground motion models have long explored the variability of ground surface motion associated with material and geometric heterogeneities of the shallow crust. Probabilistic seismic hazard practice, however, still relies on treating sites as one-dimensional layered formations and integrating epistemic uncertainty and aleatory variability associated with site response analyses by randomizing one-dimensional (1D) soil profiles. It has been recently shown that this idealization may be a poor predictor of ground motion variability at sites with strong subsurface topographic relief and heterogeneous layers with large coefficients of variation, even in cases where ground motions are too weak to induce any nonlinear effects. We present an open-source finite element computer code, Seismo-VLAB, that renders basin-scale (km) 2D and 3D site response analyses computationally feasible and procedurally seamless with engineering design procedures. We demonstrate the capabilities of the platfrom by performing basin response simulations for 2D randomized media and analyzing the statistical properties of ground surface motions that substantially differ from 1D analyses with randomized properties. On the basis of these simulations, we present a synthetic empirical model that uses non-dimensional parameters to capture the spatial variability of ground motion on the surface of these idealized basins; and we suggest how this model could inform improved parameterization of basin effects in GMMs.

Impacts of Seattle Basin on Performance of RC Core-wall Buildings During M9 Cascadia Subduction Zone Earthquakes

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United States Geological Survey and University of Washington researchers generated thirty, physics-based, ground-motion simulations that provided the opportunity to evaluate the potential impacts of sedimentary basins on building performance during an M9 earthquake on the Cascadia Subduction Zone. For periods ranging from 1.5s to 4s, the spectral accelerations in Seattle for many simulated motions exceeded the risk-targeted maximum considered earthquake (MCER) ground motions that do not account for basin effects. The period-dependent variation in the spectral amplification also led to ground motions with spectral shapes that further increased the damage potential of the ground motions.

The impacts of these motions were evaluated for thirty-two archetypes, ranging from 4 to 40 stories, representing modern residential concrete wall buildings in Seattle. The archetypes were developed to reflect the minimum requirements of the ASCE 7-16 code provisions. Maximum story drifts and collapse probabilities were computed using nonlinear dynamic analysis and a slab-column fragility function that was derived from experimental data. For motions that did not account for the Seattle Basin, the average collapse probability for the archetypes was less than 10% for an M9 earthquake. The average collapse probabilities for these buildings increased to 21% when the effects of the Seattle Basin were considered. The 50-year collapse risk was estimated by accounting for crustal, intraslab and interface events, as well as material, design and modeling uncertainties. For buildings with 4 to 24 stories, the Seattle Basin increased the average 50-year collapse risk for the reference archetypes from 0.7% to 1.8%, which significantly exceeds the target value of 1%.

Evaluation of Source and Basin-induced Surface Waves on Seismic Performance of Non Linear Structures

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The seismic design of structures currently uses a horizontally stratified (1D) case to consider site effects. Amplification factors (AF) or aggravation factors (AGF) account for the additional amplification in the translational input motion caused by two or three-dimensional response in the case of more complex sub-surface geometries such as basins. This additional amplification comes from the diffraction and refraction of seismic waves at the basin's edges or at the different sediment's layers, plus the creation of surface waves. Surface waves generate rotational components that may affect the same magnitude as translational ones, but these rotations are neglected in the calculation of AFs or AGFs. In this study, the Domain Reduction Method (DRM) is used to simulate a full 3D numerical model of wave propagation from source to structure, including non-linear soil-structure interaction, enabling all the above-described effects to be considered. Two simple basin geometries with two types of incident sources, plane wave SV and point source, have been used to calculate the amplification factors. A simplified non-linear structure (MDOF) has been placed at different positions along the basin to calculate its damage. The purpose of this study is to correlate the amplification factors and the associated damage of the structure in order to determine the influence of surface waves on the seismic performance of structures constructed over basins. According to the obtained response, higher damage was found in the structure when the subsurface configuration is present compared to the 1D case, and higher damage was associated with rotational components generated at the source, which highlight the importance of fully-coupled modelling.

Monitoring the Compaction Underneath Mexico City Using Ambient Noise

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Mexico City is undergoing subsidence due to groundwater extraction that leads to compaction of the sediments composing its upper aquitard and aquifer. We study whether the influence of subsidence on the elastic properties of the near-surface, which are highly relevant for seismic hazard, can be near-continuously monitored with (urban) ambient seismic noise.

We measure relative changes in seismic velocity (dv/v) using single-station measurements of all seismic data available on the FSDN and construct time series spanning from 15 months to 25 years. We identify mainly three signals in the dv/v time series: a seasonal variation, a rapid drop and subsequent recovery coinciding with the Puebla earthquake 2017 and a long-term velocity increase that is mainly prominent at stations in and near the zone of lacustrine clay deposits that form the aquitard ("Lake zone"). We use precipitation data and the poroelastic response model of Roeloffs (1988) to calibrate the stress sensitivity of shear wave velocity. We use a co-seismic drop and relaxation model to model the Puebla 2017 earthquake signals. Finally, we extract the rate of velocity increase at each station, which we compare to the rates of subsidence determined by remote sensing methods such as InSAR. Results suggest a spatial correlation of subsidence rate and near-surface velocity increase rate.

Analysis of Rayleigh Waves in the Sedimentary Basin of Bogotá, Colombia

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The generation of surface waves heavily influences the ground motion recorded on sedimentary basins. The damage potential that surface waves can have in civil structures demonstrates the importance of understanding and identifying specific earthquake parameters that may have the most incidence in their generation. In this study, we use the method proposed by Meza-Fajardo et al. (2015,2016) to extract the prograde and retrograde components of Rayleigh waves from accelerograms recorded in the sedimentary basin of Bogotá, Colombia. The azimuth of the surface-waves components was used to conduct k-means cluster analysis to find unknown patterns on the basin's surface wave generation from a large set of parameters. Additionally, a comparison between the maximum absolute displacement of the original recording components (North, East and Vertical) and extracted Rayleigh waves components (Radial, Transverse and Vertical) demonstrate that in several cases, the latter represents a significant part of the original records amplitude. These preliminary results show the importance of the surface waves generation in the basin and the need to advance in understanding this phenomenon to increase the data available for the development of seismic building codes, microzonation studies and seismic risk assessments of the metropolitan area of Bogotá.

Ground Motion Time Histories for Subduction Zone Earthquakes Using Artificial Intelligence

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Generating broadband acceleration time series for scenario earthquakes remains a challenging task. We apply a recently proposed algorithm that uses Generative Adversarial Networks (GANs) to train a data-driven ground motion model for subduction zone earthquakes in Japan. The model is conditioned on moment magnitude, rupture distance, hypocentral depth and Vs30, a proxy for site response, and can be applied to either interface or intraslab events. We focus on its validation by comparing its output with a semi-empirical ground motion model developed using the NGA-subduction database. We directly calculate discrete intensity measures from the synthetic accelerograms and compare them against the predictions of the semi-empirical model. We perform detailed comparisons for peak ground acceleration (PGA), peak ground velocity (PGV) and 5%-damped pseudo-spectral accelerations. We also explore the potential of the artificial intelligence approach to capture basin effects.

Sediment-basement Structure of the Northern Los Angeles Basins

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The structure of the northern Los Angeles basins is important for quantifying the seismic hazard of the surrounding megacity, and in particular, the depth of the basement is a critical factor in determining the ground shaking levels. In addition, the northern basins provide a mechanism to channel energy from a potential southern San Andreas earthquake rupture into downtown Los Angeles. The Basin Amplification Seismic INvestigation (BASIN) project conducted passive seismic surveys of the San Gabriel, Chino, and San Bernardino basins. Here, these datasets are combined with Bouguer gravity data to determine the depth of the basement. Furthermore, 14 well logs with recorded basement depths were used to constrain and validate the model.

Despite their physical proximity, the subsurface structure of the northern basins is quite different in depth and shape, which provides insight on their formation. The San Gabriel basin is the deepest basin with a maximum modeled depth of 3.5 km at the center. Another zone of significant depth is along the eastern edge of the basin. The Chino basin, generally known as a groundwater basin, is characterized by shallow depths of about 1-1.5 km and deepens to the north. The San Bernardino basin, bounded between the San Jacinto fault (SJF) and San Andreas fault, is a semi-circular shaped basin with its deepest part located closer to the SJF. Another notable depocenter of interest is north of the San Bernardino basin and east of Chino basin, which has a significant depth of 3.5 km. The fault locations with the basins have also affected their shape showing possible and ongoing interactions with basin formation.

Shear Wave Velocity Model for the San Gabriel and San Bernardino Basins From Dense-array Ambient Noise Correlation

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We construct a 3D shear wave model for the top 2-5 km of the San Gabriel (SG) and San Bernardino (SB) area based on ambient noise correlations, constrained by gravity, receiver functions and borehole data. For the correlations, we use 10 linear dense nodal arrays and a few temporary broadband stations from the BASIN (Basin Amplification Seismic Investigation) project, plus South California Network broadband and accelerometer sensors. With the correlation of different components among all the possible station pairs, we extract the Empirical Green's function (EGF) of Rayleigh (ZZ) and Love (TT) waves. To separate the Rayleigh wave's fundamental mode from the higher mode, we develop a dispersion analysis method based on the particle motion of the Rayleigh wave that combines a wavelet and Hilbert transform. With the Rayleigh and Love wave, fundamental and first higher mode, group and phase velocity EGF, we construct the 3D shear wave model for the SG and SB area. The inversion also includes Bouguer gravity and receiver functions as a priori. The velocity model is consistent with multiple geological and geophysical observations, including geological cross-sections, sonic logs, time-varying deformation from InSAR and other basin models from gravity and aeromagnetic inversions. The San Gabriel basin shows significant variations in depth with a major jump along the Raymond fault. In comparison, the San Bernardino basin is generally very shallow except in the eastern part between the San Jacinto and San Gabriel faults. The Chino basin is a less significant feature than in the SCEC CVM models.

Effects of the Los Angeles Basin on Ground Motion Studied Using Lab Experiments on a 3D-printed Model

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Despite extensive research using numerical modeling approaches, it remains challenging to simulate ground motions in the presence of small-scale features such as sedimentary basins. High-frequency ground motions that are greatly affected by the basin structure are particularly difficult to simulate; instead, they are often approximated using stochastic approaches. Such challenges in numerical methods limit our understanding of basin effects. Particularly, the 3D basin effects, i.e., consideration of the volume and shape of basins, irregular basin edges, and laterally varying basin depths, need further investigations.

We introduce a new lab-based method of ground motion simulation. We (1) build a physical model based on the Los Angeles Basin structure using the 3D printing technique and (2) conduct seismic experiments on the model by generating artificial "quakes" and measuring displacements, using a pulsed laser as seismic sources and a laser doppler vibrometer as receivers. Small-scale heterogeneities such as shallow sedimentary basins with low velocities and complex interfaces are reproduced by adjusting the speed of the 3D printing: the faster the speed, the lower the density and slower the wave speed. The velocity model contains a shallow basin with laterally varying depths between 150m and 1.5km (printed at 1:260,000 ratio). Recorded data show P and surface wave arrivals that are consistent with the input velocity model. We also observe the effects of the sedimentary basin on the ground motions. The edge of the basin reflects and scatters P and surface waves, even when their wavelengths are more than five times longer than the basin depth (150m). Likely due to the reflections, high-frequency energies are relatively reduced inside the sedimentary basin. We also present time-domain analyses on the peak ground displacement (PGD) using our displacement field recordings.

Broadband Ground Motion Simulations with Sediment Nonlinearity: A Case Study at Garner Valley, California

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We perform a series of large scale, nonlinear, earthquake ground motion simulations that account for the cyclic plastic behavior of sediments in the shallow crust. Our goal is to understand and quantitatively assess how idealized models of sediment nonlinearity influence the amplitude, frequency content and duration of strong ground motion in broadband earthquake simulations. We use the Garner Valley region in southern California as a test case where near-surface nonlinearity has been reported for peak ground accelerations (PGAs) as small as 0.05-0.2g. We model the sediment cyclic response using a multi-axial constitutive model formulated within the framework of bounding surface plasticity in terms of total stress and implemented in a high-performance computing finite element code. We first describe a series of numerical experiments designed to verify our model implementation, and then present a series of idealized large-scale simulations where material properties were extracted from the Southern California Earthquake Center (SCEC) Community Velocity Model CVM-S4.26 (using its optional geotechnical layer). The modulus reduction curves and ultimate shear strength were selected empirically to constrain the nonlinear soil model parameters. Furthermore, we simulate the rupture of the 2010 Mw 5.4 Borrego Springs and a Mw 6.5 scenario earthquakes using a kinematic earthquake rupture model. Having the rupture simulations, we then compute synthetic ground motions with the nonlinear model (for a maximum frequency of 5 Hz) and discuss how modeling shallow crust nonlinearity affects the ground response intensity measures in the different cases considered.

Verification and Validation of the Broadband Cybershake Platform Using Observations

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The Southern California Earthquake Center (SCEC) has developed the CyberShake software platform to implement a physics-based probabilistic seismic hazard analysis (PSHA) approach using 3D wave propagation simulations to calculate seismograms and ground motions from sources defined in regional earthquake rupture forecasts. CyberShake is able to quantify effects such as basin amplification and rupture directivity that are difficult to capture in conventional empirical ground motion models. Recently, CyberShake has been extended using modules from the SCEC Broadband Platform (BBP) to generate broadband ground motions up to 50 Hz in order to include frequencies of engineering interest.

Broadband CyberShake has undergone an extensive verification and validation effort against both results from the BBP and data from historical earthquakes, including Northridge, Chino Hills and Landers. For each historical event, we ran simulations on the Broadband CyberShake platform, which generates ground motions by combining results from low-frequency (≤1 Hz) deterministic finite difference wave propagation in 1D and 3D media with stochastic high-frequency seismograms (1-50 Hz), for multiple slip realizations and stations. For the verification part of the work, we compared the 1D CyberShake ground motions to those computed with the BBP, which uses a frequency-wavenumber code for low-frequency content and a stochastic code for high-frequency content. We found close agreement in 1D simulations between the CyberShake and BBP results, for waveforms, Fourier amplitude spectra and pseudo-spectral accelerations across multiple sites and realizations. We also present comparisons between 3D and 1D Broadband CyberShake results to quantify the impact of the velocity model and basin effects. Finally, we show validation results of the 3D CyberShake ground motions compared against observational data for these events.

The Effects of Sedimentary Basins on Earthquake Ground Motions

Poster Session · Wednesday 20 April · Conveners: Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov); Kristel Meza Fajardo, Bureau de Recherches Géologiques et Minières (k.mezafajardo@brgm.fr); Sean K. Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Patricia Persaud, Louisiana State University (ppersaud@lsu.edu); Chukwuebuka C. Nweke, University of Southern California (chukwueb@usc.edu); Jean-François Semblat, École Nationale Supérieure de Techniques Avancées (jean-francois.semblat@ensta-paris.fr); Fernando López-Caballero, Ecole Centrale Paris, CentraleSupélec (fernando.lopez-caballero@centralesupelec.fr)

Challenges Facing Discovery of Largest Lake in World History Geotechnical Investigation

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Earthquakes as one of important Natural hazards, has caused the destruction of Tehran (Ray civilization) in history. However, extensive studies conducted in the recent decade reject all previous findings about the cause of these incidents. Paleoseismological studies show that the escarpment of North Rey, South Rey and Kahrizak faults have no evidence of faulting but they are paleoshorelines.

Recent studies show the relation between civilizations location and the ancient Lake shorelines. This has resulted in discover of the largest ancient lake in world history. Today, the lake is known as the Paleo Mega Lake of Rey (PAMELA).

Subsidence, as the other destructive natural hazard, has also created problems for Tehran. PAMELA sediments are mostly made of clay and silt and have a high potential for subsidence if lost water. In this study, we investigate the relationship between the PAMELA sediment thickness and the subsidence rate. The method of this research is Vertical Electric Sounding to identify the depth of sediments. Then the correspondence between these findings and the subsidence data in the area is examined.

Geophysical profiles in the western part of Tehran plain show that PAMELA sediments can be traced to a depth of more than 120m to 8m in the east. This is due to the low depth of bedrock in the eastern part of Tehran plain because there is no noticeable difference in topography on the surface. On the other hand, from east to west in the Tehran plain, the rate of subsidence, according to available resources, increases from 10 cm/y to 25 cm/y. The main cause of the subsidence in Tehran plain is PAMELA sediments and changes in their thickness. Due to the high sensitivity of these clay sediments to water loss and subsidence, it seems necessary to investigate the distribution of these sediments in the whole country of Iran.

Examination of Synthetic Reno-area Basin Amplification From Small Earthquakes to 3 Hz Frequency

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Seismic waves travel with greater amplitude and slower speeds when moving through soft sedimentary rock, relative to hard bedrock. Reno's location within a thin (<1 km) sedimentary basin increases the city's seismic hazard as the basin can trap seismic wave energy and amplify ground motions. Eckert and others have recently published the results of the Reno ShakeOut Scenario, in which they simulated wave propagation for a single M6.3 earthquake to frequencies of engineering interest, >3 Hz. Last summer, we used the SW4 code from LLNL/geodynamics.org to simulate seismic wave propagation through the Reno area for six variously located M3 earthquakes, at lower frequencies. After compiling SW4 for the first time under MacOS Big Sur for Apple's new M1 chip, we ran the code on personal laptops to complete each scenario with substantial wave energy up to 0.74 Hz. We then used PGV maps produced from these scenarios to compare shaking at basin versus bedrock sites and how it changes based on the location of the earthquake. Similar to Eckert and others, we found that there are large PGV basin amplification factors at low frequencies. The amplification factors show great spatial variance, particularly when accounting for the choice of five possible bedrock stations around Reno. In order to obtain a non-ergodic view of basin amplification in Reno at 3 Hz frequencies, we used an allocation for 20,000 core-hours through NSF-XSEDE to run one of our original six low-frequency scenarios to a maximum frequency of 3.125 Hz through Eckert's velocity model. Preliminary indications are that basin amplification and spatial variance both grow as frequency increases. These results will help in determining the basin's amplification effects when assessing seismic hazard in the Reno area and other urban basins.

Joint Velocity Inversion of Active-source Phase Velocity Dispersion and Ambient-vibration H/V Spectral Ratios in the Atlantic Coastal Plain Sediments, Eastern US

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The Atlantic Coastal Plain of the eastern U.S. south of New York City is underlain by flat sediments that extend as much as 300 km inland. These sediments cause substantial amplification of seismic waves, particularly at fundamental resonant frequencies that depend on sediment thickness and velocity. Many urban areas lie atop these sediments, making their effects on ground motions a concern for seismic hazards. Velocity measurements are sparse, especially at greater depths. Here we carry out a joint inversion of phase velocity dispersion curves from active sources and Horizontal-to-Vertical spectral ratios (H/V) from ambient noise to estimate the velocity structure across the Coastal Plain sediments in Virginia and North Carolina. Dispersion curves are from dynamite shots recorded on over 700 receivers spaced ~300 m apart during the 2015 Eastern North American Margin (ENAM) refraction experiment. H/V curves are from a coincident passive deployment of 80 seismometers in 2014. We use a joint inversion method with a genetic algorithm optimization procedure to estimate 1-D velocity profiles. The method uses initial random velocity models constrained by lithology, and forward modeling determines the model that best fits the observations. The best-fit model in each generation is retained, and new generations of models are created from the nearby parameter space. The procedure is iteratively repeated over 500 generations to improve the fit to observational constraints. Results show a shallow layer in the upper ~100 m with velocities of 200 to 450 m/s and a thickness that appears to be independent of the overall sediment thickness. Velocities in the deeper portions of the sediments, below about 600 m depth, are in the 600 to 1500 m/s range, with velocity contours being nearly horizontal and cutting across ACP lithologic contacts. The results suggest that depth of burial rather than lithology is the primary factor influencing velocities in the Coastal Plain sediments.

Model Surface Wave Dispersion Analysis Across a Basin Boundary

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A common occurrence through the geotechnical and engineering communities is that assessments for ground and building response to earthquakes are completed using 1D modeling in situations that are multidimensional. This simplification has complex implications in areas such as the Basin and Range where the 3D basin structure that can be seen in shallow shear wave modeling causes varying amplification effects on seismic shaking. Three lines of deep ReMi data were taken in west Reno, Nevada where a vertical displacement in the velocity contours of approximately 350 m was revealed along the north-to-south oriented arrays. Two synthetic 1D models were created using the high and low-velocity profiles found within the ReMi data set. A third, 2D model was created where the top 250 channels to the north represent the 1D low-velocity model and the southern 250 channels represent the 1D high-velocity model, creating an east-west boundary between the two. The 3D SW4 wave-propagation computational models employ a virtual linear, north-to-south array of 500 geophones with 10 m spacing surrounded by an omni-directional arrangement of eight virtual sources activating every 3 seconds for a total of 30 seconds. Synthetic Rayleigh dispersion results from 0.5 to 7 Hz on the 1D velocity models follow the input models with accuracy that is better than 10%. The 2D high-velocity array reaches velocities only as high as the 1D high velocities at shallow depths of 50 to 100 m. The central 2D low-to-high velocity crossover array gives an average to low-velocity result. Dispersion modeling of the velocity values reveals the best dispersion fit and the lowest RMS fit values belonged to the 2D low-velocity array. Additional basin edge effects can be identified throughout the synthetic records and the slowness-frequency plots.

Paleo Mega Lake of Rey Sediments and Its Effect on Earthquake Acceleration Case Study Tehran City

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The severity of the damage in the earthquakes depends on various factors; one of the most important reason is the geological condition of sites i.e. the distribution of Quaternary sediments. These sediment layers control seismic impedance related with the velocity and density of the layers in the ground. Because of the amplified ground motion amplitudes, seismic impedance can play a major role in the rate of the destruction of structures. A good example of the sediment effect on increased earthquake damage is the case of southern part of Tehran. According to early studies on the tectonics of the region, the North Rey, South Rey and Kahrizak faults were supposed to be the cause of these damages. However, the more recent Paleo Mega Lake of Rey (PAMELA) theory suggest that the tectonic structures in North Rey, South Rey and Kahrizak are the lake shoreline.

This study investigates the effect of the spatial distribution of alluvium on the seismic hazard level of Tehran using a shear wave velocity map. The USGS global shear wave velocity map is modified using the geotechnical and geological data. PAMELA sedimentological data, which are silt and non-hardening clays, have also been used to modify the Vs30 map of the study area. The results of seismic hazard analysis in this region apparently illustrate the effect of shear wave velocity on the variation of hazard level. The resulted hazard maps illustrate that the inverse relationship between hazard level and shear wave velocity clearly emerges as an east-west trend in the south of Tehran plain. The higher peak ground acceleration values gained from the seismic hazard results around the escarpments of the PAMELA shoreline are due to accumulation of soft sediments. Therefore, the acceleration, regardless of the distance from the fault, is amplified by reaching these sediments and the amplification of seismic waves in these sediments is supposed to be the main reason for the destruction of the ancient city of Rey in the past ages.

Preliminary Shear-wave Velocity Site Characterization at Strong Motion Stations in Anchorage, Alaska, Using a Flexible Multimethod Approach

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We evaluate shear-wave velocity (*Vs*) structure at 19 strong motion stations in the Anchorage, Alaska, region using a flexible multimethod site characterization approach. The acquisition sites were located throughout the City of Anchorage and northward through the Eagle River and Palmer-Wasilla areas. We acquired two colinear active-source, 72-sensor linear array surface seismic datasets (1.5 m sensor spacing) at each site: one with single-component (1C) 4.5 Hz vertical and one with 1C 4.5Hz horizontal sensors. We also deployed one 20s-to-100 Hz three-component (3C) broadband seismometer and a set of five 4.5 Hz, 3C sensors for microtremor horizontal-to-vertical-spectral-ratio (mHVSR) and microtremor array (MA) analyses, respectively. We analyze the active-source horizontal-component field records for both SH-wave refraction traveltime and Love wave dispersion, whereas the vertical-component records were analyzed for Rayleigh wave dispersion and P-wave refraction traveltimes. For our preliminary *Vs* characterization, we combine the active-source dispersion and traveltime datasets and model them using an iterative least-squares joint inversion method. At several sites, the vertical-component Rayleigh dispersion data were difficult to interpret and are thus not yet incorporated into this preliminary analysis. We adjust weighting of the independent datasets based in part on data signal quality. Our preliminary analyses yielded time-averaged *Vs* to 30 m depth (V_{S30}) in the 200 to 720 m/s range; these values are broadly consistent with previous observations in the Anchorage region and their locations align with the spatial distribution of National Earthquake Hazard Reduction Program site classifications from B to D previously estimated across the city. Sites located nearest the range front on the eastern side of Anchorage tended toward higher V_{S30} values. Once integrated with the mHVSR and MA datasets, our *Vs* profiles will be used in support of ground motion modeling in the region.

Revision of Iranian Seismic Design Code for Tehran Region Based on “Paleo Mega Lake of Rey” Theory

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Tehran, as one of the most populous cities in the world, is surrounded by several active faults. The destruction of this city has been reported many times in the historical records. The most important factors that played a role in these destructions have usually been taken to be the three active faults named North Rey, South Rey and Kahrizak, which have the shortest distance with the Rey civilization in the south of Tehran. Recent findings suggest that these three faults are in fact the remains of the shores of an ancient lake that covered the Great Desert. In this study, a seismic hazard assessment has been fulfilled with an updated seismic source model (North Rey, South Rey and Kahrizak are eliminated from the seismic sources of the region). Prehistoric and historical earthquakes data were analyzed according to previous paleoseismological studies. The new statistical analyses of the region were also obtained from the most updated earthquake databases derived from the ISC catalogue for the period from 1900 to 2021. The updated seismic parameters are utilized to implement the seismic hazard assessment in the bedrock level.

Comparison of the results of the updated hazard assessment with the Iranian Seismic Design Code according to soil types show major changes on spectral acceleration in the metropolitan area. In the southern part of the city, from Rey to Robat Karim, the PGA of the ground motion has dropped sharply at the bedrock level. Thus, the updated PGA values are reduced by up to 40% compared to the Iranian seismic design code. The reason for this reduction is the elimination of these three faults from the region. Analyses show that the theory of the Ancient Mega Lake of Rey has had a dramatic effect on changing the earthquake acceleration in Tehran. If the seismicity code of the area is revised based on this study, the principles of seismic engineering construction will change completely.

Sediment Thickness and Ground Motion Site Amplification Along the United States Atlantic and Gulf Coastal Plains

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Past and present research on earthquake ground motions along the Atlantic and Gulf Coastal Plains and Mississippi Embayment show significant period-dependent site response that is not presently accounted for in the ground motion models that are applied in the current U.S. Geological Survey National Seismic Hazard Model (NSHM). These deviations are strongly correlated with the thickness of Mesozoic and younger syn- and post-rift sediments. With the recent incorporation of deep basin depth measurements in the NSHM for select regions in the western United States, we move toward a similar analysis in the greater Coastal Plains region by: (1) creating a comprehensive ground motion database; (2) constructing a sediment thickness model; and (3) considering multiple new site response models conditioned on sediment thickness—including Harmon and others (2019), Pratt and Schleicher (2021) and Chapman and Guo (2021).

As of the preparation of this abstract, we have prepared a ground motion database consisting of 25,483 records of period-dependent Fourier and response spectral amplitudes from 265 events occurring between February 2010 and December 2020 measured at 2,657 stations and performed a preliminary evaluation of the Chapman and Guo model. We find that the predicted ratio between pseudo-spectral accelerations for the Coastal Plains relative to the continental interior are broadly consistent with our independent dataset. However, our analysis reveals complex spatial- and period-dependent ground motions across the CEUS, and we continue to investigate how well existing models can account for these patterns.

Sediments Thickness Correction in GK17 Ground Motion Modeling

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I am discussing implementation of sediments thickness effect in ground motion modeling and its incorporation in ground motion prediction equations (GMPE) for the 5%-damped acceleration response spectra. Sediments thickness effect adjustment based on the depth to the shear-wave velocity horizon of 2.5 km/s ($Z_{2.5}$) is presented for the GK17 (Graizer, 2018) ground motion model. Complete sediments thickness correction is a combination of sediments thickness correction embedded in the V_{S30} correction and additional correction for sediments shallower than 0.6 and deeper than 3.2 km. Sediments thickness effects increase long period (>0.2 s) ground motions for depths larger than 0.6 km and decrease long period motions for smaller $Z_{2.5}$ depths. Deep sediments typical for basins can significantly amplify ground motions, while a significant portion of the site amplification is already incorporated in model's V_{S30} correction. I am recommending using sediments thickness correction term instead of basin effect when applied to current use in GMPEs. This can help avoiding confusion and misunderstanding when comparing to basin effect in seismology because 1) none of the Z-terms represents actual basin depth, 2) basin-edge effect is not considered, 3) actual shape of basin is not considered. I found out the best fit between V_{S30} and $Z_{2.5}$ to be power approximation $ln(Z_{2.5})$=7.52-1.23ln(V_{S30}), where $Z_{2.5}$ is measured in kilometers and V_{S30} is in m/s.

The San Gabriel and San Bernardino Basin Project: New 3D Velocity and Structural Models in the Los Angeles Region for Improved Ground Motion Estimates

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This presentation summarizes the BASIN (Basin Amplification Seismic Investigation) experiment and its analyses. The goal of the project is to produce a better structure and velocity model for the San Gabriel and San Bernardino basins on the northern edge of Los Angeles, in order to enable better prediction of the ground motions from a large earthquake rupture on the southern San Andrea fault. Simulations of these earthquakes using ambient noise correlations (Denolle et al., 2014) have shown that current Southern California community velocity models under predict ground motions by a factor of four.

The BASIN results are based on 10 dense linear arrays of nodes deployed over a three year period. Receiver functions (Ghose et al.) produced a set of layer interfaces including the sediment-basement interface and Moho. These were extended from a mesh of 2D lines to a fully 3D grid by incorporating Bouguer gravity data (Villa et al.). The recordings at each of the nodes were correlated with each other and with the Southern California Seismic Network (SCSN) stations and temporary broadband stations, to produce empirical Greens functions. These were used to estimate the group and phase velocities of both Rayleigh and Love waves, which were then used to invert of the shallow shear wave velocity structure (Li et al.). This process was constrained by the basin depth measurements from our studies and a few borehole logs that penetrated basement. The product of this study is a mesh of basement and Moho depths and a 3D grid of the shear wave velocities down to 2 km.

Comparative Analysis of Body- and Surface-wave Amplification in the Seattle Basin

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Seismic hazard in the U.S. Pacific Northwest (PNW) is controlled by multiple seismic sources, including large interface (M>9) and intraslab earthquakes in the Cascadia Subduction zone, as well as shallow crustal earthquakes. Cities within basins, such as Seattle, can experience basin amplification, which increases the amplitude of long-period (T>1 s) seismic waves that affect tall buildings and other structures. Current crustal ground-motion models for the region rely on earthquake records from other regions because of the paucity of records from moderate- to large-magnitude events in PNW, and the newly developed subduction ground-motion models do not account for basin-amplification differences from shallow (interface) and deep (intraslab) earthquakes. Here we present analyses of basin amplification to compare the effects from vertically propagating S-waves and from surface waves, which may have important controls when waves enter the basin laterally from larger distances. We calculate body- and surface-wave amplification factors for sites within the Seattle basin and within the broader Puget Lowland region, relative to reference sites outside of the region, using Thompson-Haskell propagator matrices and recently developed semi-analytical surface wave methods, respectively. The methods are applicable to 1D seismic velocity profiles and linear-amplification regimes. Calculations make use of the Cascadia community seismic velocity model. We find that amplification factors show strong sensitivity to the velocity profile of the reference site, particularly where reference sites have high shear-wave velocities near the surface. By correcting the profiles at reference sites with high shear-wave velocities, we find that resulting amplification factors become comparable with empirical estimates. Spatial patterns of the body- and surface-wave amplification patterns show distinct differences, as do their scalings with basin depth. This work aims to further explain differences in basin-amplification models that may ultimately be used to improve understanding of earthquake hazards.

Everything Old Is New Again—Resurging Use of Analog Data

Poster Session · Thursday 21 April · Conveners: Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Peggy Hellweg, University of California, Berkeley (peggy@seismo.berkeley.edu); Richard D. Lewis, Defense Threat Reduction Agency (richard.d.lewis1.civ@mail.mil); Qi Ou, University of Oxford (qi.ou@earth.ox.ac.uk)

A Directory for the Discovery of Legacy Seismic Data

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Legacy seismic data is an important primary data set of observations of seismic events that occurred in the past century. Using new methods and applying new insights and discoveries, careful reuse of these data has furthered our understanding of seismogenic processes. However, much of this data remains undiscoverable to a generation of digital seismologist. Accessing physical seismograms from collections often requires retrieval from hard to access facilities. In recent years, recognition of the fragile state of many collections and the emphasis on FAIR data has led to a renewal in efforts to preserve these collections digitally for future use. Efforts are underway to establish minimal metadata and best practices for the preservation of these growing collections. However, to be FAIR, the data not only need to be open licensed and available, they must also be discoverable.

To aid researchers in the discovery of legacy seismic data, we have created a directory that provides information about available resources. The goal is to assist in the discovery and access of legacy seismic data collections worldwide. Legacy seismic data is any data related to the operation of seismic networks that were not collected originally in digital form. This includes seismograms, station bulletins, phase cards, among other artifacts. The initial stage of the project focuses on seismogram collections originally recorded on paper but can include data recorded on other media such as FM tape. We present information from publicly available sources about seismograms that are available in digital format typically as digital images. Interactive maps show available data by station, event, and managing organization and provide a starting point to access additional information on the resource as well as references in the literature. In building a community for FAIR legacy data, we seek contributions and feedback in developing this open-source project as a valued community-maintained resource.

Nuclear Explosion Legacy Data in Central and Eastern Europe

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Leidos team recently finalized the first step of a data legacy rescue project for nuclear explosion data recorded in Central and Eastern Europe, via a Department of State sponsored project. It was based on a process of inventory, identification, scanning and aggregation of metadata and data quality control, followed by collecting the scans and their associated metadata into a common repository to prevent potential loss of information. Around 2,000 analog seismograms for 300 nuclear explosions detonated during 1965 and 2017 and recorded at 57 stations located at distances 5-156 degrees were scanned and their associated metadata were collected. Digitization software packages presently available were tested on some of the scans. Valuable experience was gained on data scanning procedures as well as on collecting, organizing and storing the metadata on station, instrument and analog recording itself, all needed for a successful usage of legacy data. All data and metadata are now stored in the Nuclear Explosion Legacy Data (NELD) database designed by Leidos, with a similar structure as that of the International Data Centre of the Comprehensive Nuclear Test-Ban Treaty Organization's Preparatory Commission.

Recovery and Digitization of Soviet Peaceful Nuclear Explosions From Legacy Analog Seismograms

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The Geophysical Survey of the Russian Academy of Sciences and Michigan State University are recovering, scanning and digitizing the historic analog seismograms of Soviet Peaceful Nuclear Explosions (PNEs). The Soviet Union detonated 122 PNEs from the mid-1960s through the late 1980s. The PNEs were conducted in a wide range of geologic settings and geographic locations, thus representing a unique data set for geophysical studies. These explosions were well recorded by the regional seismic networks, where thousands of seismograms are still retained. We are working to index these irreplaceable legacy analog seismograms and preserve them against loss for future generations. In the process, we are also generating high resolution scans of the seismograms and digitizing them for analysis. Along with the seismograms, we are recovering the original station calibrations, responses and metadata for each station and developed code to generate Dataless SEED files for use with the digitized data. Most seismograms are from short period instruments and when combined with the correct station calibration information, the digitization process accurately recovers ground motion signals to at least 5 Hz. The resulting digital waveforms are of sufficiently high quality that they are usable for quantitative research.

Revisiting the M7.3 1948 Ashgabat Earthquake Using Historic Seismograms and Satellite Imagery

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The 1948 M 7.3 Ashgabat earthquake, killing over 38,000 people, occurred in the dextral strike-slip Kopeh Dagh fault zone in the Iran-Turkmenistan border region. Previously, it has been debated which fault(s) it occurred on and whether this earthquake was a thrust/reverse, strike-slip, or multi-fault earthquake, as published focal mechanisms suggest it had a reverse mechanism. We relocated the hypocentre using 24 historical seismograms and ISS phase arrival data. We present a new strike-slip focal mechanism from new first motion polarity and P/SH amplitude ratio data. We use Pleiades satellite stereo imagery to produce Digital Elevation Models of part of the ruptured area. These data reveal clear strike-slip faults where surface ruptures were mapped in 1948. The earthquake did not rupture the Main Kopeh Dagh fault, but instead these subsidiary faults, highlighting the importance of considering lesser faults in seismic hazard models.

The ISC Electronic Archive of Printed Station and Network Bulletins

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The International Seismological Centre (ISC, www.isc.ac.uk) has recently launched a new service, the ISC Electronic Archive of Printed and Network Bulletins (Di Giacomo et al., 2021), which is openly available on the ISC website. The archive allows users to look for scans of instrumental seismic bulletins containing parametric data of either a single station or a set of stations (network). The search for scans is based on the location of the town of an institution that produced a bulletin. As such, the electronic archive is easy to use and is likely to facilitate the work of a wide community interested in studying past earthquakes and involved in preservation and digitization of analogue recordings. We shall provide examples illustrating this service.

Although the ISC archive is likely to be the most comprehensive of its kind, we know that many more bulletins could be added and certain gaps in scans could be filled. Hence we invite contributions from archives around the world as well as from individual investigators that wish to preserve and allow use of printed bulletins to the geoscience community for years to come.

References: Di Giacomo, D., Olaru, D., Armstrong, A., Harris, J. and Storchak, D.A. (2021). The ISC Electronic Archive of Printed Station and Network Bulletins, Seism. Res. Lett.; doi: https://doi.org/10.1785/0220210262

WFNE Repository and Nuclear Explosion Legacy Data

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The "Waveforms From Nuclear Explosions (WFNE)" repository was developed and is maintained by Leidos under DTRA sponsorship. It was built as a trusted data set, starting from the previous data repository "Nuclear Explosion Database (NEDB)" that was accessed in the past by numerous users in USG agencies and by the US and international nuclear explosion monitoring community. WFNE includes detailed information (origin, bulletin, other geophysical data) on all the 2,157 atmospheric, underground and underwater nuclear explosions detonated in the world during 1945 and 2017 and their associated waveforms and station/instrument information, as collected from many sources. Presently, WFNE is being updated, modernized, improved and rendered ready for active access by USG and USG contractors, as well as by non-USG Contractors and other entities. Adding data from new sources is part of present work. Recent efforts on rescue of pre-digital seismic data via scanning and digitization provide interesting data to be added to WFNE, after completeness and quality checks.

Examining Digitization Parameters to Produce High Quality Data from Historical Analog Seismograms

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The recovery and digitization of legacy seismograms is critical for research of historical seismological events. Analog seismogram digitization is a difficult and complex problem and requires standards to successfully recover information from the analog media. This study investigates proposed standards for the digitization of analog seismograms. For this investigation, we utilize synthetic 'white noise' seismogram with known frequency content that emulates an analog record. The synthetic signal can be modified to test variables such as scan resolution, interpolation algorithms, amplitude, line thickness, etc. After digitization, the digital seismograms are compared back to the original synthetic seismogram. We tested multiple interpolation algorithms and with our manual digitizations we find application of Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) interpolation algorithm improves the quality of the digitization and minimizes the amount of distortion. We quantify the effectiveness of scan density by the ease of digitization and waveform accuracy. Low scan resolutions adversely affect waveform accuracy and ultimately the frequency recovery. For example, a 200 DPI image can recover signals up to about 2.5 Hz whereas a 600 DPI image can recover up to about 8 Hz, assuming an original recording speed of 60 mm/s. Variability of the signal width can change due to the focus of the recording beam/pen. Wider signal traces reduce the probability of accurately recovering high frequency signals due to hidden signals in the overlapping traces. If a signal thickness is more than twenty times the trace width, recoverable frequencies from 7–10 Hz can be expected. We observed the recoverable signal from low amplitude analog traces. Signals that exceed five times the width of the analog trace can be recovered within 3db of the true reference amplitude.

Exploring Earthquake Source Dynamics and Wave Propagation Properties in Tectonic and Lab Environments

Poster Session · Wednesday 20 April · Conveners: Rohtash Kumar, Banaras Hindu University (rohtash21@bhu.ac.in); Subhash C. Gupta, Indian Institute of Technology, Roorkee (s.gupta@eq.iitr.ac.in); Ranjit Das, University Catolica Del Norte (ranjit.das@ucn.cl); Prithvi Thakur, University of Michigan (prith@umich.edu)

Characteristics of Pulse Duration and Amplitude of P-wave Seismograms

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Understanding the characteristics of pulse durations (τ_P) and amplitudes (A) of P-waves is of importance because they can be used to estimate the maximum intensity of ground motions, earthquake magnitudes, faulting mechanisms and earthquake locations, all of which are crucial for earthquake early warning. Previous studies (e.g., Harrington & Brodsky, 2009; Kanamori & Brodsky, 2004; Kikuchi & Ishida, 1993) calculated τ_P of source-time functions (STFs) of the ground motions recorded in several regions (e.g., Japan, California) and proposed correlations between τ_P and earthquake moment magnitude (M). Wu et al. (2006) and Hsiao et al. (2011) also investigated correlations between A and the magnitude.

In this study, we measured the τ_P and A of initial pulse from the seismograms recorded at the seismic stations in Korea and Japan, and conducted regression analyses for τ_P and A with various parameters such as M, epicentral distance (R_{epi}), the time-averaged shear-wave velocity for the upper 30 m of soil deposits (V_{S30}), fault type and seismogenic zone type. We used a total of 514 seismograms recorded during the M 0.7–5.8 events at Korea Meteorological Administration stations and 364 seismograms recorded during the M 1.9–9.0 at Kiban-Kyoshin network stations. We calculated the time duration from P-wave arrival time to the first zero-crossing point after the arrival time as the τ_P. We defined the A of P-wave pulse as the peak value of velocity within the time interval between the P-wave arrival time and the first zero-crossing point. We observed that the τ_P and A increase with increasing M, which are consistent with previous studies. We also observed that the τ_P increases, but the A decreases with increasing R_{epi}. However, the τ_P and A don't show significant trends with V_{S30}. Moreover, the P-wave pulses from normal faults and subduction zones have longer τ_P and larger A than those from reverse and strike-slip faults and shallow crustal zones.

Fully-automated Processing of Single- and Multi-peak Microtremor HVSR Measurements Using Machine Learning

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The horizontal-to-vertical spectral ratio (HVSR) of microtremor measurements is a site characterization technique for rapidly and inexpensively estimating a testing location's fundamental resonant frequency (f_0). HVSR has been deployed successfully at the local and, with considerable effort, city scale. However, the deployment of HVSR at the regional scale, while possible, remains challenging due to the significant direct human interaction required by traditional HVSR processing approaches. The reliance of these approaches on manual human interaction not only requires the dedication of significant time and resources when considering large scale datasets but also introduces the potential for significant bias in the results and significantly reduces future reproducibility by other analysts. These disadvantages are especially true for HVSR measurements with multiple peaks, as the interpretation of such measurements remains challenging even for highly-trained analysts. The peril of misinterpreting multi-peak HVSR is compounded by recent work that shows multi-peak HVSR may be linked to more complex subsurface conditions and elevated seismic hazard. Therefore, there is a strong need for a HVSR processing workflow that strongly limits, or preferably removes, direct human interaction and is cable of extracting estimates, with measures of uncertainty, for f_0 from HVSR ($f_{0,HVSR}$) and other resonant peaks if they are present. In response, tools from artificial intelligence and machine learning, in particular Gaussian mixture model clustering coupled with gradient boosting, have been applied successfully to remove manual human interaction in HVSR processing and fully automate the extraction of single- and multi-peak HVSR. These findings represent a significant step forward in the advancement of HVSR processing, allowing it to be rapidly and reproducibly applied to large regional-scale datasets. The author hopes that this work will contribute to the further standardization and reproducibility of HVSR processing.

Ground Motion Prediction Models for Pennsylvania From Industrial Seismic Sources

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Local to regional distance shear-wave observations of mine blasts are used to investigate frequency-dependent ground motion prediction models for the state of Pennsylvania. Previously, attenuation relations were constructed for eastern North America using ground motion recordings of small-to-moderate magnitude earthquakes observed across broad regions. Associated studies showed variations in attenuation with distance that deviated from an r^{-1} dependence near the source and at the transition from local to near-regional distances. Pennsylvania hosts a substantial number of mining-related seismic events each year, and a notable number of seismic stations operate within the state and bordering states. Although observations from shallow explosive sources are not ideal for assessing potential shaking resulting from earthquakes (deeper shear-faulting sources), we exploit the available observations to construct empirical estimates of ground motion prediction equations for the region. We analyze 2,286 industrial events (M < 3) recorded from 2013 to 2021 using approximately 1,400,000 seismograms and measure the peak ground velocity of S-wave amplitudes across multiple frequency bands. Not all seismograms provide high-quality observations but were recorded on seismic stations operational during industrial activity. We use regression to estimate piecewise continuous attenuation (geometrical spreading and attenuation), site, and source terms to construct a frequency-dependent ground-motion propagation model to compare with existing ground-motion prediction relations for the eastern United States.

Mapping Active Faulting in Post-mining Induced Seismicity by Network-based Waveform Similarity Analyses and Moment Tensor Inversions

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During operation and after the closing of underground mines, induced seismicity represents a potential hazard. In the latter case, it most often appears to be correlated with changes in the groundwater table, either caused by natural phenomena or pumping activities. Seismicity can act as a precursor of gallery collapses. However, it can also be related to the reactivation of pre-existing faults triggered by pore pressure transients. The seismic hazard accompanying the flooding of a mine is poorly known and usually not included in post-mining risk management policies. While most seismic events are not felt, larger induced earthquakes might be a concern for the local population in industrialized mining regions, where underground mines are often located below or close to populated areas. These concerns can be addressed by studying the subsurface processes to identify and counteract the triggering processes. A first step towards understanding the subsurface processes is the characterization of the induced events and the mapping of activated faults. We study the induced seismic activity in an abandoned flooded coal mine in Gardanne, southeast France, which was exploited until 2003 and gradually flooded afterward. We propose a combination of full-waveform moment tensor inversions for the largest events with a network-based waveform similarity cluster analysis. Based on the clustering approach, we examine a data set from Gardanne, which was recorded by a sparse temporary monitoring network between 2014-2017, while we invert for moment tensors for more recent events after the enhancement of the monitoring network. Subsequently, we can match clusters persisting over time and infer mechanisms of smaller events within the early phase when the monitoring suffered from a limited station availability.

Probabilistic Constraints on the Southern Californian Seismic Energy Budget From Heat Flow Across the San Andreas Fault

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Long-term seismic hazard assessment currently benefits from balancing long-term estimates of crustal deformation with the accumulated deformation of seismicity. The usual approach balances crustal strain rates with a long-term model earthquake frequency distribution, using seismic moment as the intermediary. An alternative approach is possible based on conservation of energy (ENCOS, Ziebarth et al., 2020, JGR). The energy balance approach requires a coupling factor, the average seismic efficiency η, that describes which fraction of the elastic energy stored by deformation becomes seismic waves. Then the energy magnitude distribution can be balanced with energy input. Constraints on η are needed to reduce uncertainties in estimating the earthquake rates.

In the ENCOS framework, the crustal deformation is measured in accumulating elastic power P. The lack of an observed strong heat flow anomaly across the San Andreas fault implies an upper bound on the dissipated power that maps into a constraint in P-η-space. This bound excludes low efficiency and high elastic powers on the fault. We employ a Bayesian approach based on a gamma distribution model of regional heat flow1 to map uncertainties in plausible anomaly strength to the P-η-space. This can act as a prior for an ENCOS model of fault seismicity. Finally, we explore how this constraint on the San Andreas fault relates to a regional seismicity model of Southern California.

Radiation-pattern Effects in Bay Area Ground-motion Models

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The ground-motion variability of earthquakes can be attributed to source, path and site effects. Empirical ground-motion models (GMMs) currently lack the proper separation between the source and path effects because the S-wave radiation pattern is not modeled as an input parameter and is assumed to have isotropic properties. The variability of the source is modeled as an azimuthally independent between-event residuals resulting in radiation-pattern effects being mapped into variability in path terms (within-event residuals). The reason GMM developers have made this simplification is that, for large-magnitude events at short distances (M>6, R< 50 km) which are important for seismic hazard, the ground motion at a given rupture distance is more sensitive to the slip distribution and rupture timing than to the average radiation pattern from the subevents along the rupture; however, for small-magnitude events, the radiation pattern can be clearly seen in the ground motions. Using the within-event residuals from 14 small-magnitude (M3.5-M4.9) earthquakes in the Bay Area, we find a significant correlation of the within-event residuals for response spectral periods between T=0.5 seconds and T=5 seconds with radiation pattern. The radiation pattern is computed using the square root of the vector sum of the SH and SV far-field radiation pattern from a regional 1-D crustal velocity model. This correlation is important for developing non-ergodic GMMs with 3-D path effects because ground motions from small-magnitude events are used to provide constraints on the linear site terms and path terms due to the 3-D crustal structure. If the radiation pattern is not included in the GMM for small magnitudes, then the estimation of the site terms and 3-D path terms will be obscured by the radiation-pattern effects. By including the radiation pattern in the GMM for small-magnitude events, the 3-D path effects are isolated from the radiation-pattern effects and the resulting 3-D path effects can be applied to large-magnitude earthquakes.

Temporal Variation of Qc and Its Implications in Medium Characterization

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The heterogeneities in the medium play an important role not only in earthquake genesis, but also strong ground motion simulation due to its bearing on attenuation characteristics. Observational data is one of the prerequisites for such studies which are acquired through deployment of seismological networks in active seismic regions. The Himalaya is considered as one of the most seismically active region in the world. It is also source of many river valley projects, like Tehri dam and others. The Tehri dam with 260.5 meter height is highest dam in India, located in the Lesser Himalaya of the Garhwal Himalaya that lies in seismic zone IV as per the seismic zoning map of India. Besides this, a number of development activity such as road and railway infrastructures are in progress. Thus, there is need to understand the effect of physical state of media on propagation of seismic waves in the Himalayas. The medium/path characteristics of this region have been measured by determining the seismic wave attenuation of high frequency waves of local earthquakes which is accomplished by estimating the quality factor of coda waves (Qc). In the present study, Qc, has been determined using local earthquakes recorded during last fourteen years from 2008 to 2021. The local earthquakes used in the study have been obtained through the deployment of 12 to 18 stations local seismological network around Tehri dam reservoir. The results showed in the study that there is no significant change in Qc is observed in the region during this period after dam impoundment. These results found in agreement with the findings that no reservoir trigger seismicity is observed in the region associated with Tehri dam reservoir during last fifteen years.

Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere

Oral Session · Thursday 21 April · 4:30 PM Pacific

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Development of Balloon-based Seismology for Venus Exploration

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Seismology has been crucial for the understanding of the interior structures of the Earth, Moon and Mars. Detailed knowledge of the interior structures of terrestrial planetary bodies is an integral part of understanding the formation of the inner solar system. On Venus, high surface temperature and pressure present a difficult technological challenge to traditional seismology. In recent years, balloon-based seismology through the study of low-frequency seismo-acoustic signals (infrasound) has gained acceptance as a viable way to study seismic activity on Venus. Balloon-based barometers have the potential to detect and characterize atmospheric waves launched by venusquakes and volcanic eruptions while offering substantially longer instrument lifetimes in the Venus middle atmosphere, where temperature and pressure are significantly more benign (0-100°C, ~1 atm) as compared to the surface (> 460°C, ~90 atm). A balloon-based investigation of Venus quake and volcanic activity can also serve as a pathfinder for highly-targeted missions involving long-lived surface seismometers in the future. In addition, auxiliary data collected to discriminate seismic infrasound from other naturally occurring sources can contribute valuable in-situ data to study important atmospheric science questions on Venus.

Our presentation will discuss the development of balloon-based seismology for Venus exploration, including the detection artificial and natural earthquakes from freely-floating high-altitude balloons, sensor miniaturization efforts and signal processing advances. We will also provide perspectives on the challenges facing the implementation of this technique on a Venus balloon and our plans to address these challenges.

Analysis of Thermal Moonquakes Within the Apollo 17 Lunar Seismic Profiling Experiment

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Although there are thousands of thermal moonquakes recorded within the Apollo 17 Lunar Seismic Profiling Experiment (LSPE), little is known about their source mechanism. Thermal moonquakes of different risetime characteristics are observed, but there is no clear consensus on their relationship to surface processes besides a correlation with lunar day/night transitions. Poor data quality has hindered algorithm development and systematic cataloging, so studies assessing moonquake location typically use only a few dozen hand-selected sample events. We recently developed a machine learning algorithm to obtain a thermal moonquake catalog of the Apollo 17 LSPE, demonstrating that this legacy lunar seismic data could be revisited with these new methods to further expand the knowledge lunar surfaces processes. We expand work on the LSPE dataset by building automatic algorithms to extract important waveform characteristics, classify, and locate the thermal moonquakes within the LSPE seismic data.

First, we use time- and frequency-domain signal-processing algorithms to calculate precise arrival times, emergence, and peak ground velocity for each thermal moonquake in the catalog. Then, the moonquake arrival azimuth is determined by applying stochastic gradient descent on a misfit equation based on the relative arrival times of the seismic signal at the array. We find that emergence, PGV, and azimuth are strongly correlated with the lunar day-night cycle. Impulsive events are correlated with the direction of the lunar module descent vehicle and principally occur during temperature transitions, but also are observed during the night and day. The events not linked to the lunar module are real moonquakes driven by a separate source and thermal properties and are observed to increase in emergence with higher regolith temperature.

An Update on the Seismicity of Mars as Recorded by InSight's Marsquake Service

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Over 3 Earth years since the InSight lander arrived on Mars and despite growing power challenges, the seismic data collection from the SEIS seismometer package is now well into a second martian year, and SEIS continues to exceed performance expectations in terms of the observed minimum noise. The Marsquake Service is tasked with creating and curating the seismicity catalogue for Mars. To date over 1250 distant marsquakes and a similar number of events likely associated with near-source thermal cracking have been identified. The background noise recorded by SEIS is strongly sensitive to local winds, whose strength and duration is changing across the martian year, though there is remarkably similarity between martian years. Marsquake signal amplitudes remain small and marsquakes can generally only be detected during the quietest periods that mostly occur during the evenings. For many regional marsquakes, crustal or mantle body phase arrivals are readily identified and used to determine distances and magnitudes. However, polarised energy is rarely observed in marsquakes, so estimates of back azimuths, and hence also event locations, are limited to only 10 events so far. Here, we review the seismicity seen so far on Mars, in terms of location, magnitude, magnitude-frequency distribution, tectonic context and possible seismic sources. We highlight the similarity of marsquake rates seen between the 2 martian years. We focus on characteristics of significant recent high amplitude high quality events that locate both close to the lander as well as on the other hemisphere.

Lateral Variations of the Martian Crustal Thickness From Insight Measurements and the Observed Gravity Field

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By using arrival times of body waves recorded by the very broadband seismometer SEIS from the InSight mission, 1D average models of the crust, mantle and core of Mars have been inferred [1, 2, 3]. However, possible causes of seismic wavefield disturbances such as 3D structure, undeniably complexify the interpretation as a 1D radial model. Because the InSight lander and the origin of marsquakes are located close to the crustal dichotomy between the Southern and Northern hemispheres, significant lateral variations of the relief along the crust-mantle interface and the surface topography can potentially affect the seismic wave arrival times.

To estimate the extent to which the seismic wave arrival times could be altered due to the lateral variations of the crustal thickness and surface relief, we generated 3D crustal models following the approach developed by [4], using the observed gravity field as constraints. The marsquake locations (back azimuth, epicentral distance and depth) and radial seismic velocity models are inferred from the arrival times of body waves using a Bayesian approach. Two different parameterizations are considered: a classical approach based on seismic profiles using Bézier curves [5] and a parameterization in terms of quantities that govern the thermo-chemical evolution of Mars, which accounts for 4.5 Gyr of planetary evolution [5, 6]. In addition to constraining the thickness of the crust at the seismic sources, our approach reveals the variability of the interior models due to data uncertainties.

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Constraints on the Crustal Structure of Mars From P- and S-receiver Functions and Ambient Vibrations Autocorrelations

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The crustal structure of terrestrial planets holds important clues on how these bodies formed and differentiated, as well as on their thermal and magmatic evolution over billions of years. For Mars, the uncertainty on the average crustal thickness was larger than 50% in the absence of direct seismic measurements and no information on crustal layering was available. We aim to close this gap in knowledge using data from the broad-band seismometer on NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission. With the mission well into its third year, we calculate P- and S-wave receiver functions for 12 and 10 marsquakes, respectively, as well as vertical component ambient vibration autocorrelations. These data sets are complementary, in that receiver functions extract converted phases from teleseismic events, whereas the autocorrelations provide information on P-wave reverberations. We expand the initial marsquake dataset [1] by a factor of 3 to 4, which allows drawing more robust conclusions, e.g. by consistently identifying two conversions in S-receiver functions and by including PPs-receiver functions of a recent distant marsquake for a larger spread in move-out.

The constraints that result from amplitude stacking of direct phase arrivals and multiples, using both receiver function data sets and the autocorrelations, for layer thicknesses and P- and S-wave velocities beneath the InSight landing site in Elysium Planitia are currently under investigation. Using orbital constraints from gravity and topography, the crustal thickness measurement at the InSight landing site can be extrapolated to map the Moho depth across the whole planet. We discuss implications in terms of global crustal thickness, crustal composition and porosity, distribution of heat producing elements and present day heat flux.

[1] Knapmeyer-Endrun et al., Science, 2021, doi:10.1126/science.abf8966

Extraterrestrial Seismology: Seismology from Mars, the Moon and Everywhere

Poster Session · Thursday 21 April · Conveners: Ceri Nunn, Jet Propulsion Laboratory, Caltech (ceri.nunn@jpl.nasa.gov); Angela G. Marusiak, Jet Propulsion Laboratory, Caltech (angela.g.marusiak@jpl.nasa.gov); Aisha Khatib, University of Maryland (akhatib1@umd.edu)

Classifying Deep Moonquakes Using Machine Learning Algorithms

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The Apollo Lunar Surface Experiment Package (ALSEP) recorded lunar seismic activity continuously between 1969 and 1977. These seismic data provided observations of deep moonquakes (DMQs), which manifest as repeating tidally-linked signals from sources located in geographically tight regions in the lowermost lunar mantle, called nests. Sources from the same nest have similar waveforms, distinct from events originating in other nests. The identification and classification of DMQ events in the ALSEP data was initially conducted using visual inspection of day-long seismograms. Computational advancements enabled the identification of more DMQs through new techniques, e.g. waveform cross-correlation and cluster analysis. Here we explore the potential of convolutional neural nets (CNNs) to identify DMQs and associate them with specific source nests.

Previously, we used a CNN to identify and classify deep moonquakes from clusters A1 and A8 based on their spectrograms. We trained several CNNs to identify the difference between A1 and A8 DMQs. Seven different models were trained and tested on the spectrograms; however, despite various modifications to the CNN architecture, the validation accuracies do not increase beyond 70%, indicating that the algorithms are not learning effectively. We postulate that the relatively poor performance of CNNs is due to the loss of phase information in spectrogram construction. Therefore, here we test the performance of 1D CNN on a synthetic dataset of events. Synthetic waveforms are computed for the Apollo 12 seismic station using a lunar velocity model and source locations from DMQ clusters A1 and A8. The synthetic traces of these seismic events were used to train a 1D CNN with better results: the CNN's training and validation accuracy both increased and plateaued at 90%. Using observed waveforms of A1 and A8 events, we compare the performance of the CNN trained on synthetics to those trained on real data. The 1D CNN approach could also be used on powerspectral and phase data to gain insight into the relative importance of amplitude and phase information in classification performance.

Constructing an Earthquake Site Response Model for the Lunar South Polar Region

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High resolution images and altimetry data from the Lunar Reconnaissance Orbiter spacecraft have allowed detailed mapping of young thrust faults on the Moon. The locations of these faults can now be combined with our understanding of evidence for and characteristics of recent activity along faults, the impact crater production rate, newly developed lunar seismic ground motion scenario ShakeMaps and data from the Apollo-era seismic network on the nature of the lunar subsurface. These data collectively offer the components needed to develop a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon. In this study we explore preliminary applications and extensions of existing PSHA methods (e.g., as utilized in the nuclear industry and more broadly) to probabilistically assess seismic hazard on the Moon and other planetary bodies. Here we focus on constructing a preliminary model of the site response component of the hazard for the south polar region using lunar stratigraphy derived using Apollo teleseismic records and regional geologic maps as a guide. The results will provide a preliminary understanding of near-surface properties important for estimating the site response needed to construct a PSHA for the Moon and also offer an improved understanding of near-surface stratigraphy on the Moon. This earthquake site characterization information is essential to support the future design and construction of structures, systems and components (especially possible nuclear-based power source options) and is particularly timely in light of renewed interest in the lunar surface operating environment and NASA's Artemis lunar exploration program and as a tool to identify information needs in support of the development of future lunar seismic monitoring networks.

Deep and Shallow Quakes in the Presence of a Clathrate-lid on Titan

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Seismic wave propagation through icy moons can potentially reveal the interior structures of icy ocean worlds. Observation of seismic sources may also be the best tool to determine the "vital signs" (fluid flow induced ground motion) of these worlds. Saturn's moon Titan is of particular interest as it is the second largest moon in the Solar System and contains both an atmosphere and a subsurface ocean. The Dragonfly rotorcraft is currently planned to launch in 2027 and land on Saturn's moon Titan in the mid-2030s. The rotorcraft itself is a dual-quadcopter that would hold many instruments, including a seismometer and two geophones, within the DraGMet (Dragonfly Geophysics and Meteorology) instrument package, to measure ground motion. For this study we simulate a range of models both shallow and deep (3, 25, 411 and 525km) within Titan while varying the methane clathrate lid thickness, in order to study the expected seismic signal from a single station seismometer on Titan.

We generate 1D synthetic waveforms for a 100 km ice shell (total thickness) with varying source depths, ranging from within the top ice shell to the deep within Titan's interior, totaling twelve, 2D spherically symmetric Titan models. Preliminary results suggest that the clathrates create minor differences in seismic phase arrival times and changes to the waveforms. The outcome of the seismic models is highly dependent upon inputs into the PlanetProfile model of Titan. Future models will explore other species of clathrate hydrates (ie. ethane), as well as adding surficial organic material layers. In addition to expanding the seismic catalog to regional-scale 3D seismic meshes of Titan's interior to include topography and a variety of heterogeneities within the ice shell (eg. fractures, melt lensing, etc).

Detection of Seismic Events Originating from Europa's Silicate Interior

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Europa, a moon of Jupiter, likely has a seismically active surface ice shell (1). It is currently unknown if Europa's silicate interior is capable of producing seismic events, here referred to as euroquakes. We investigate if a euroquake could be detectable by surface instrumentation. We use PlanetProfile (2) to generate geophysical models with ice shells ranging from 5-50 km thick. The models are used as inputs for AxiSEM (3) and Instaseis (4) to generate seismic waveforms with event depths of 3 and 155 km, representing shallow euroquakes in the ice shell and deep euroquakes in the silicate interior. The AxiSEM databases are also used to generate realistic noise models (5). We compare the ground motions of surface to deep events to quantify the reduction in amplitudes. We then compare deep euroquake amplitudes to seismic background noise to determine the minimum magnitude of an observable. The peridograms of euroquakes are compared to several seismic instruments noise levels (6,7) to determine the magnitude required for instruments to detect the events. Lastly, we show how signal strength and ability to detect deep euroquakes is dependent on ice shell thickness. Our results show the reduction in ground motion depends on ice shell thickness with thin ice shells reducing ground motions by a factor of 10 while thicker ice shells reduce ground motion by a factor up to 170. A magnitude 3.5 or 4.0 is needed to overcome background noise, depending on distance and thickness of the ice shell. A magnitude 4.5 could be seen by sensitive instrumentation, if the ice shell is relatively thin. However, a magnitude 5.0 or 5.5 is necessary for a deep euroquake to be globally visible on the less sensitive instruments.

1. Hurford *et al.* Icarus 338,113466 (2020); 2. Vance, *et al.*, *JGR Planets*. 123, 180–205 (2018); 3. Nissen-Meyer, *et al.*, *Solid Earth*. 5, 425–445 (2014); 4. van Driel, *et al.*, *Solid Earth*. 6, 701–717 (2015); 5. Panning, *et al.*, *JGR Planets*. 123, 163–179 (2018); 6. Nunn, *et al.*, *Planet. Sci. J.* 2, 36 (2021); 7. Lognonné, *et al.*, *Space Sci. Rev.* 215, 12 (2019).

Investigating the Heterogeneous Nature of the Deep Martian Mantle With Geodynamically-constrained Inversions of InSight Seismic Data

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The recent identification of deep reflected phases in the seismic recordings of the InSight mission as core reflected phases have led to the first seismic detection of the Martian core [1]. These results indicated that the core size of Mars spans the higher end of InSight pre-mission estimates, implying the presence of a substantial amount of light elements in the core.

The presence of well-separated silicate and metallic enveloppes indicates that Mars experienced an early global magma ocean stage whose crystallisation likely led to the formation of a compositionally distinct layer at the bottom of the mantle [2]. Such a layer is expected to be heavily enriched in heat-producing elements and in iron, leading to long-term stability with little mixing between the layer and the overlying mantle. The presence of this enriched basal layer often yields the development of a molten silicate layer above the core [3] that could act as a deep seismic reflector.

To investigate the compatibility of deep Martian mantle layering with seismic data we conducted Monte Carlo Markov chain inversions in which the long-term thermo-chemical history of Mars' main envelopes is embedded into the forward problem. This results in thermal structures at present-day that are converted into seismic structures [4]. This approach considers an enriched silicate layer above the core-mantle boundary. We used the most recent travel time dataset that contains considerably more shallow and deep phases compared to previous studies. Altogether, this allows us to test the hypothesis of the presence of a molten layer at the top of Mars' core, along with the associated consequences on the interpretation of seismic, geodetic and geochemical data.

[1] Stähler, S., et al., Science 373, 443–448 (2021); [2] Elkins-Tanton et al., JGR., doi: 10.1029/2005JE002480 (2003); [3] Samuel, H. et al., JGR, doi:10.1029/2020JE006613 (2021); [4] Drilleau, M. et al., G. J. Int., 226, 1615-1644 (2021)

Lunar Gravitational-wave Antenna

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Lunar Gravitational-wave Antenna (LGWA) proposes to deploy an array of next-generation seismometers on the Moon. This network will measure the lunar surface displacement excited by Gravitational waves (GWs) with a targeted observation band of 1mHz – few Hz.

The absence of atmospheric and oceanic excitation keeps the seismic noise in that frequency band several orders of magnitude below terrestrial seismic noise. Therefore, this fundamental advantage of the Moon makes it an ideal target for GW detection experiments. The choice of using cryogenic technology and deploying the network in one of the PSRs (Permanent Shadow Regions) of the Moon will make it possible to detect expected displacement on the order of 10-15 m/rtHz at 1 Hz.

The scientific and technical challenges of LGWA are diverse. Since its initiation, LGWA has relied on experts from fundamental physics, astrophysics, geophysics, engineering and planetary science. The collaboration is currently organized in working groups (WGs) to cover five key themes: GW science, lunar science, payload, deployment and operations. We will introduce science and engineering challenges of the LGWA concept, and we will discuss the ongoing activities of the collaboration.

Mars Interior Revealed From Over Three Years of InSight on Mars

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InSight has been operating on the surface of Mars since November, 2018, with a focus to investigate the interior of a planet using geophysical data acquired from its surface. It has three primary instruments: SEIS (a seismometer), RISE (which utilizes the spacecraft's X-band transponder) and HP^3 (a device for measuring regolith thermal gradient and conductivity), which focus on seismic, planetary rotation and heat flow measurements, respectively. The secondary instruments (IFG, a magnetometer; PS, a pressure sensor; and RAD, a ground-viewing infrared radiometer) and support equipment (two cameras and a robotic arm) that were included to optimize the primary instruments have proven to be scientifically valuable as well, both in terms of their independent observations and synergies with other measurements.

While all these instruments have produced key results for understanding Mars and terrestrial planets more generally, we will focus here on the seismic results from crust to core. Among other approaches, the physical properties of the upper few tens of cm have been studied through travel-time analysis of seismic waves excited by HP^3 hammering. Elastic compliance measurements enabled by joint observations of atmospheric vortex effects by the PS and SEIS provide constraints on the regolith elastic properties of the upper meter to several 10s of meters. The elastic properties of the region from 10 meters to a few hundred meters has been resolved through inversion of high-frequency Rayleigh waves. Seismic receiver function and auto-correlation techniques have yielded the structure of the crust down to several tens of km, and sophisticated body wave travel time studies have probed the mantle structure to depths exceeding 600 km. Finally, the identification of core reflected phases in marsquake signals detected by SEIS and confirmed by the measurement of the subtle nutations in Mars' rotation by RISE have revealed the size and density of the core.

Fault Damage Zones: What We Know and Do Not

Oral Session · Wednesday 20 April · 2:00 PM Pacific

Conveners: Alba M. Rodriguez Padilla, University of California, Davis (arodriguezpadilla@ucdavis.edu); Travis Alongi, University of California, Santa Cruz (talongi@ucsc.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Thomas Mitchell, University College London (tom.mitchell@ucl.ac.uk)

Seismic Imaging of the Mw 7.1 Ridgecrest Earthquake Rupture Zone and Garlock Fault From Data Recorded by Dense Linear Arrays

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We analyze seismograms recorded by five arrays with 100 m station spacing and apertures of 2–8 km that cross the surface rupture of the 2019 Mw 7.1 Ridgecrest earthquake (from B1 in the NW to B4 in the SE) and the adjacent Garlock fault (A5). For the Ridgecrest earthquake rupture zone, the results show complex internal structures (velocity contrasts and low-velocity zones) that vary along fault strike. Both teleseismic and local P waves travel faster on the northeast than the southwest side of the fault beneath arrays B1 and B4, but the velocity contrast is less reliably resolved at arrays B2 and B3. We also identify several 1–2 km wide low-velocity zones with much slower inner cores that amplify S waveforms, inferred as damage zones, beneath each array. The damage zones at arrays B2 and B4 also generate fault-zone head and trapped waves. The trapping structure around array B4 has, based on waveform modeling of stacked trapped wave, a width of ~300 m, depth of 3–5 km, S wave velocity reduction of ~20% with respect to the surrounding rock, Q-value of ~30, and S wave velocity contrast of ~4% across the fault (faster on the northeast side).

Clear P waves reflected from the Garlock fault, oriented northeast-southwest near the southern end of the Ridgecrest rupture zone, are observed at array B4 and identified for 7 events with depths ranging from 4 to 10 km. The polarity of fault zone reflected waves suggests that P waves travel faster in the crustal block north of the Garlock fault. This is in agreement with large-scale tomography models, and results of P-wave delay times of local and teleseismic events, along with fault zone head waves resolved at array A5. We hand-pick good quality reflected signals and image a vertical dipping angle of the Garlock fault interface between 2-6 km via Kirchhoff migration. A ~300-m-wide low velocity zone centered on the Garlock fault is also identified from P wave delay times, but no persistent S wave amplification pattern or fault zone trapped waves are detected, likely due to the complicated surface geology beneath array A5.

Tomography of the Ridgecrest Fault Region Using Aftershocks as a Network of Virtual Seismometers

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Using interferometry, aftershocks of large events can be treated as a network of virtual seismometers to allow detailed measurements along the fault trace. The Virtual Seismometer Method (VSM) is a technique that provides precise estimates of the Green Function (GF) between earthquakes (Curtis et al., 2009; Hong and Menke, 2006). This isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features, such as at depth in active fault zones.

In July 2019, two large earthquakes occurred during the Ridgecrest earthquake sequence along with thousands of smaller events. These smaller events, recorded by the dense Southern California network and well located in space and time, are ideal for VSM anaylsis. We calculated VSM waveforms for over 1600 paths between events within the Ridgecrest swarm and used them to jointly invert for seismic parameters (Vp, Vs, Qp and Qs) and to create a localized image of structure from the surface down to about 12 km depth.

We observe lateral heterogeneities in velocity and distinct features both along and across the major fault trace. The seismicity generally occurs where velocity gradients are highest and in areas of relatively low Vp/Vs. The major fault segments are defined by high shear attenuation, with the exception of the northwestern-most aftershock zone. This northwest region has distinctly higher velocities, significantly higher Qs and very low Qp/Qs ratio and

appears to be tectonically distinct from the rest of the sequence. The low Qp/Qs values in this region are indicative of subsurface fluids.

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Ambient Noise Tomography of the Ridgecrest Fault Damage Zones: What We Know and Do Not

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We perform ambient noise tomography using data recorded from Nodal arrays within a ~50 km by 50 km area including the July 2019 M7.1 and M6.4 Ridgecrest, CA, earthquakes. The imaging uses a locally sparse tomography (LST) approach with unsupervised dictionary learning and least-squares regularization that directly learns from local patches without requiring a large volume of training data. We also derived a 3D shear velocity model of the area, which is obtained from surface wave dispersion inversion and reveals a highly heterogeneous low-velocity zone (LVZ), with the primary velocity reduction in the upper 2-3 km, around the causative faults for the M7.1 and M6.4 events. The 1-5 km wide LVZ of shallow low S-wave velocities are reduced by about 40% relative to the host rock surrounding the fault traces for the M7.1 and M6.4 events. The LVZ is correlated with the extent of the distributed faulting as mapped by differences between daily passes of the PlanetLabs Satellite imagery, suggesting a possible causative relationship between the imaged LVZ and the 2019 Ridgecrest rupture sequence. Other imaged LVZs in the model area is correlated with parts of the Little Lake Fault System without recent activity, which may indicate long-lasting damage zones.

Using Active Source Seismology to Image a Strike-slip Fault Damage Zone as a Function of Depth, Distance and Geology

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Fault damage zones provide a window into the non-elastic processes and products of an earthquake. Existing geological and seismic tomography methods and observations have not measured damage zones at depth with sufficient spatial sampling to evaluate the relative influence of depth, distance and lithological variations. Here, we identify and analyze the damage zone of the Palos Verdes Fault offshore southern California using two 3D seismic reflection datasets. We apply a novel algorithm to identify discontinuities attributed to faults and fractures in large seismic volumes (~ 10^8 points) and examine the spatial distribution of fault damage in the sedimentary rock surrounding the Palos Verdes Fault. Our results show that damage is most concentrated around mapped faults and decays exponentially to a distance of 2.2 km, where fracturing reaches a clearly defined and relatively undamaged background for all examined depths (450m to 2.2 km) and lithologies. This decrease in fracturing with distance from the central fault strand has a similar functional form to outcrop studies. However, here we extend analysis to distances seldom accessible. Separating the data by geologic units, we find that each unit's damage decay and background level differs. The lack of systematic change in damage among progressively deeper sedimentary units suggests that lithology is a more important control on damage than depth. Qualitatively less brittle units, such as siltstone, have damage that decays rapidly with distance and has low background damage levels, and the opposite is true for sandstone and conglomerate. Surprisingly, these differences in damage decay and background level balance each other out, resulting in a consistent damage zone width regardless of lithology or depth.

Fault Damage Zone Effects on Near-field Ground Motions in a Multi-scale Dynamic Rupture Model of the 2019 Ridgecrest Sequence

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We compare near-field ground motions of two multi-scale dynamic rupture models of the 2019 Ridgecrest sequence including the M_w 6.4 Searles Valley foreshock, followed by the M_w 7.1 Ridgecrest mainshock 34 hours later. Both models incorporate a complex 3D non-vertical fault geometry, 3D velocity structure, high-resolution topography, 3D initial stress distribution and off-fault plasticity. Frictional failure is described by a strong velocity weakening rate-and-state friction law. One model is complemented by a shallow flower structure fault damage zone, which represents a homogeneous approximation of the 0.5-1.5km wide "intensely damaged inner core" identified by Qiu et al. (2021). The macroscopic properties of the fault zone are simulated by reducing seismic velocities by 30% and elastic moduli accordingly. Those parameters are indicative of an endmember case of an immature fault damage zone.

The rupture dynamics are only mildly affected by the fault damage zone, therefore ground motion differences between both models are mainly attributed to wave propagation effects. Peak horizontal velocities (PHVs) of the fault zone model are amplified mostly by 50-100% above rupturing faults. But the trapping of seismic energy also shields certain areas from strong ground motions, which can lead to PHV reductions of more than 50%. For example, recorded ground motions at station CCC (RJB = 2km) appear significantly impacted by fault zone shielding effects. The analysis also shows that the fault zone impact is not limited to the direct vicinity of the fault system but still widely affects ground motions at distances of more than 50km to the rupturing faults, which indicates its high relevance for seismic hazard assessment. The relative influence on ground motions is sensitive to the portion of frequency content overlapping with the eigenfrequencies of the fault zone structure. Consequently, it depends on the corner frequency of the source spectrum and thereby on magnitude.

Acceleration and Coalescence of Damage Zone Seismicity Leading Up to Large Earthquakes

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Fault damage zones comprise multiple fractures which can generate seismicity in response to mainshocks, tectonic loading, or other stress perturbations, and in turn modify the stress state on the main fault. The physical processes controlling seismic swarms, and their implications for the time-dependent seismic hazard posed by the mainshock fault, are not fully understood.

Here we study the precursory phase of large earthquakes in a fault zone comprised of a rough (fractal) fault surrounded by damage, represented as a collection of smaller faults with a power-law decay of density with distance from the main fault. We model seismic cycles assuming uniform velocity-weakening rate-state friction and loading by a uniform far-field stressing rate.

We find that during the interseismic period between large ruptures on the main fault, seismicity takes place predominantly in the damage zone and it is clustered in episodic swarms. Seismicy rates increase prior to the mainshock and exhibit a clear migration towards its hypocenter, both along strike and across the fault zone; in other words, seismicity becomes more localized in the final phase of the seismic cycle. This coalescence is controlled by two processes: 1. recovery of negative stress changes imparted by the previous mainshock, which are largest in the near field; 2. a triggering cascade in which each successive event is more likely to occur closer to the main fault, due to the power-law increase in fracture density towards the main fault.

In addition to foreshocks, simulations exhibit aseismic slip in subparallel secondary faults. We find that the mainshock is triggered by stress changes from both foreshocks and aseismic slip in the damage zone and occurs earlier than it would have on a planar fault without damage.

Fault Roughness and Frictional Stability Control Seismic Energy Partitioning Between Fore, Main and Aftershocks During Laboratory Stick-slip

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The average behavior of large populations of earthquakes, including aftershocks, is well described by simple statistical relationships. However, predicting individual aftershock sequences is complicated because of poorly understood triggering mechanisms, crustal stresses and fault zone properties.

We untangle contributions from mainshocks and fault zone properties to the generation of aftershocks during slip on rough and smooth faults at upper crustal stresses in the laboratory. Our experiments lead to complex fault slip behavior, such as transitional aseismic slip, stable sliding and stick-slip (analogous to natural faulting), which are well-described by stiffness, stress and friction. Experimental conditions close to frictional instability lead to seismicity statistics (e.g. waiting time and spatial distributions) that are indistinguishable between lab and nature. Smooth faults within the unstable frictional regime produce power-law seismicity rate increase before slip but essentially no aftershocks. Rough faults, on the other hand, show no simple acceleration of seismicity to failure but highly productive aftershock sequences, particularly when residual stresses are high. We conclude that seismic energy partitioning between fore, main and aftershocks is controlled by surface friction and fault roughness.

A Geodetic Constraint on Seismic Velocity Changes in Fault Damage Zones

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Seismic velocities are known to reduce around the vicinity of a fault. This reduction is often characterized by the existence of a fault damage zone, the structure and property of which, indicate the maturity of the fault and affect future co-seismic rupture process. There has been lots of seismologic studies that reported such reduction and vp/vs ratio changes along many faults. Here we present a geodetic approach on constraining the structure and velocity changes in fault damage zones. When earthquake stress release causes compliant deformation on its nearby faults, one could detect these motions with high-resolution InSAR acquisitions. With the deformation profiles, the width of the fault damage zones could be directly measured. Using a fault slip model, we could then estimate the strain conditions across these compliant faults. We input these into a finite element fault zone model to fit the fault-parallel and vertical deformation profile by changing the depth extent of the damage zone, its shear modulus reduction and Poisson's ratio. The depth extent is constrained by the decay of the deformation profile outside of the damage zone, while the horizontal amplitude is controled by the shear modulus reduction. Given these two parameters, one could further change the p-wave velocity to get the right amplitude for vertical deformation. Compared to seismic analysis that is usually limited by the resolution, this geodetic approach is mostly definitive.

Fault Friction Derived from Fault Bend Influence on Coseismic Slip During the 2019 Ridgecrest Earthquake

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Constraining the variation of stress on faults is important for improving our understanding of fault friction and the dynamics of earthquake ruptures. However, we still have little observational constraints on their absolute magnitude or their variations in space and in time over the seismic cycle. Here we use a new geodetic imaging technique to measure the 3D coseismic slip vectors along the 2019 Ridgecrest surface ruptures and invert them for the coseismic stress state. We find that the coseismic stresses show an eastward rotation that becomes increasingly transtensional from south-to-north along the rupture, that matches the known background stress state. The stress model also shows the ruptured faults near the M_w 7.1 mainshock hypocenter were critically stressed and that the slip magnitude scales almost linearly with how well aligned the fault is to the initial stress field. From assuming Mohr-Coulomb failure we find the absolute magnitudes of shear stresses range from 4-8 MPa in the shallow crust and that faults have an intermediate static strength (frictional coefficient of 0.49) but requires dynamic weakening with a reduced frictional coefficient of 0.23 to explain slip observed along sub-optimally orientated faults.

738,000 Years of Off-fault Damage at the Volcanic Tablelands

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Measurements of the cumulative deformation history of a fault are challenged by incomplete knowledge of pre-faulted markers, sparse data coverage and limited chronologies. Using recently collected high-resolution lidar data of the Volcanic Tablelands in California, we image and analyze zones of permanent deformation associated with flexure of the hanging wall and footwall of normal faults cutting through the Bishop Tuff. High strains are localized to narrow symmetric zones (50-300 m) surrounding faults. These zones have average bending strains of ~10^{-2} and exhibit constant width along most of the fault length, narrowing at the fault tips. The extent of off-fault deformation is independent of the thickness of the faulted unit, which decreases from ~100 m to ~60 m from east to west. Instead, the width of high-intensity off-fault deformation scales with fault throw following a power-law. Our observations suggest that the extent of off-fault flexural folding is rheologically controlled and directly constrains the area of influence of off-fault plastic processes.

Fault Damage Zones: What We Know and Do Not

Poster Session · Thursday 21 April · Conveners: Alba M. Rodriguez Padilla, University of California, Davis (arodriguezpadilla@ucdavis.edu); Travis Alongi, University of California, Santa Cruz (talongi@ucsc.edu); Xiaohua Xu, University of Texas at Austin (xiaohua.xu@austin.utexas.edu); Thomas Mitchell, University College London (tom.mitchell@ucl.ac.uk)

Characterization of Damage Zone Structure Along the Elsinore and Superstition Hills Faults: Towards Quantification of Mmax

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The structure of damage zones associated with the Superstition Hills and Elsinore faults in Southern California faults varies substantially in terms of size and fracture density despite being formed in similar lithologies in the same tectonic environment. These have hosted earthquakes up to Mw6.6 (20 cm coseismic slip) and Mw6.8 (150 cm coseismic slip), respectively. We are studying the micro- and mesoscale structure of these fault damage zones to investigate the possibility that the damage zone structure preserves information about the maximum earthquake magnitude (or displacement) hosted by each fault. We conducted fieldwork of outcrops at Imler Road where it crosses the Superstition Hills fault in the Palm Springs Formation and at the mouth of Fossil Canyon where the Elsinore Fault cuts the Imperial formation. The fossiliferous sandstones of the Imperial formation are largely solidified compared to the Palm Springs formation which mainly consists of poorly lithified non-marine sandstone, with thin interbeds of strongly indurated sandstone. We collected oriented samples for microstructural analysis at both sites and mesoscale damage zone fractures up to 410m from the Elsinore and Superstition Hills faults using high-resolution photomosaics. We mapped fractures on top of the photomosaics and analyzed the resulting vector graphics data to resolve spatial variations in the damage zone structure. The damage zone is expressed at the Elsinore Fault in Fossil Canyon as deformation bands that form as clusters around smaller faults, superimposed on microscopic damage at the grain scale. The Superstition Hills fault is primarily expressed by joints and small faults in poorly consolidated sands, with significantly less damage at the grain scale and no apparent deformation in strongly lithified sands. We discuss the implications of the differences in damage zone structure for interpreting the role of past earthquake ruptures on off fault deformation at each fault locality.

High-resolution P-wave Velocities Across the Creeping Section of the San Andreas Fault at Mee Ranch, Central California

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We present a tomographic P-wave velocity model along a seismic profile across a creeping section of the San Andreas fault at Mee Ranch in central California. Our objectives are to evaluate seismic velocities, lithology and groundwater variations within the fault zone. The ~500-m-long profile was orientated roughly perpendicular to the active fault trace and was recorded by

395 3-component nodal seismometers spaced at 1- or 2-m intervals. P-wave shots were co-located (within 0.5 m) with the seismometers and were generated using a 227-kg accelerated weight drop. All shots were recorded by all nodes for a total of almost ~100,000 traces. Our preliminary model shows a sharp lateral velocity gradient below 30 m depth, with lower velocities (1,000-2,800 m/sec) on the southwest side to higher velocities (1,000-3,500 m/sec) on the northeast side of the active fault. Overall velocities range from < 1,000 m/sec at the surface, to > 3,000 m/sec at 100 meters depth but vary laterally by as much as 700 m/sec over about 100 meters distance at the near-surface active trace of the San Andreas fault. S-wave data were also collected along the profile, which will allow for determination of Vp/Vs and Poisson's ratios to better characterize the physical characteristics of the near-surface fault zone.

Internal Variations of the Banning and Mission Creek Fault Zones Near the Thousand Palms Oasis Preserve From a Large-N Seismic Array

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The southern San Andreas fault (SSAF) has the highest estimated 30-year probability for a M ≥ 6.7 event of any major fault in California, yet key structural characteristics of the SSAF remain unclear, including fault zone attitudes and dimensions and the partitioning of slip and strain between the Banning (BF) and Mission Creek (MCF) faults. To address these questions, wavefield variations from local earthquakes were analyzed across an array of 322 three-component seismic nodes deployed near Thousand Palms Oasis, California. The array consisted of two 2D subarrays with 0.6-1 km apertures centered on the BF and MCF and a ~4 km quasi-linear profile transecting both strands. In this high-resolution study, we divided each subarray approximately in half at the fault strands' surface traces and beamforming was performed on early P waves propagating across each subarray half. This process was applied to >100 events recorded at the BF subarray and >200 events at the MCF subarray, yielding beams representing P wavefront arrivals on either side of each fault strand. Beams crossing the MCF appear to have generally smaller azimuth and slowness differences between subarray halves, but beams crossing the BF from the south and southwest show azimuth differences of >100° and slowness differences of up to 0.2 s/km. These differences imply a strong P-wave velocity contrast across the BF and less pronounced P wave velocity variations across the MCF. Future work will include ray tracing and fault zone velocity perturbations to determine the amount and placement of low-velocity material required to produce these beams, and the analysis of potential seismic anisotropic properties within these fault zones. Quantifying these characteristics will yield information about the relative maturity and activity of the BF and MCF, and, in turn, may help improve seismic hazard assessments of the SSAF.

Long-distance Propagation of Guided Waves Along Ridgecrest Faults and Evaluation of Connectivity With the Owens Valley and Garlock Faults

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Some previous studies suggest that guided waves do not propagate more than about 10 to 15 km from the epicenter of earthquakes, but our study provides evidence that guided-wave propagation can be several times farther, particularly when two or more individual fault segments are connected at depth. We use aftershocks of the 2019 Ridgecrest earthquake sequence to investigate long-distance propagation (~ 50+ km) of guided waves and connectivity of the Ridgecrest causative fault with the Garlock and the Owens Valley faults. From aftershocks located near the northern end of the 6 July 2019 Mw 7.1 Ridgecrest earthquake rupture, we observe guided waves that propagate progressively southward past several fault-perpendicular seismic arrays, with the most distant array located greater than 50 km from the epicenter. From aftershocks located near the southern end of the Mw 7.1 surface rupture, we also observe long-distance northward propagation of guided waves along the Mw 7.1 Ridgecrest earthquake causative fault and southwestward propagation along the Garlock fault, suggesting the two faults are connected. We also evaluated possible guided waves that were generated by aftershocks on the northernmost Mw 7.1 Ridgecrest causative fault and recorded on the Owens Valley fault. We observed high-amplitude arrivals that are consistent with guided waves at mapped traces of the Owens Valley fault, suggesting it is connected to the Mw 7.1 Ridgecrest causative fault. If these faults are connected, it suggests that the entire fault system is much longer than the individual faults, with implications for a larger maximum-magnitude earthquake on the fault system.

Margin-scale Damage Zone Along the Queen Charlotte Fault

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Damage zone widths around strike-slip faults occur on scales that are thought to be proportional to the total displacement, but this has not been observed at the scale of continental margins. Damage zones on this scale however, play an important role in the seismic hazard for those who live proximal to the fault. A salient example would be the San Andreas Fault, located along coastal California, where complex deformation surrounding the main fault represents a significant seismic hazard for the large population that lives adjacent to the fault zone. The San Andreas Fault however, has a complex deformation history and is exposed to erosion, making it difficult to map the damage zone on continental scales. In our study we use the Queen Charlotte Fault, the northern counterpart of the San Andreas Fault, to map the damage zone around the fault on a continental scale. The Queen Charlotte Fault (QCF) is an ideal study site because it lies along the continental-oceanic boundary where the oceanic crust has a relatively simple deformational history that is preserved due to its position at the seafloor.

In our study, we used a combination of gravity, magnetics and seismic reflection datasets to map the oceanic crust on the west side of the QCF and obtain a first order constraint on the limit of the damage zone. We found that the damage zone is on the order of 20 km wide. We also mapped the static stress perturbation within the oceanic crust due to variations in fault orientation along the fault to show that the damage zone is correlated with a high-stress envelope surrounding the fault, suggesting that geometric variations at length scales of 150-200 km are related to damage zone width. This study provides additional insight into the width of damage zones on larger scales that can be important to understanding the seismic hazards along strike-slip continental margins.

Mid-crustal Structure of an Exhumed, Multiply Reactivated Proterozoic Plate Boundary: Active-source and Borehole Seismic, Geologic Mapping and 3D Microgravity in the Homestake Shear Zone, Colorado

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The Proterozoic Homestake Shear Zone (Rocky Mountains, central Colorado, USA) typifies tectonic inheritance. Beginning ~1.6 Ga as a transpressive suture between the southwestern margin of Archean North America and accreting Yavapai terranes, it has reactivated ductilely, brittly and epeirogenically seven times since, most recently in the early Tertiary Laramide orogeny. Bedrock units—mainly biotite gneiss and similar felsic to intermediate metamorphics—now at ~3 km elevation have been exhumed from about 15 km. This project focuses on a ~4-km section (along-strike, NE–SW) about 1 km wide centered on Homestake Creek. Detailed mapping demonstrates not two but three Quaternary(?) glaciations that preferentially scoured NE-trending shears. Geotechnical borings were completed to ~30 meters depth at 16 locations to provide in-situ constraints on bedrock depth, lithology and fracture distribution. Puzzlingly, a majority of both borehole and outcrop fractures strike NNW-SSE, perpendicular to every mapped structure in the area and to the shear zone itself, parallel to the downstream face of myriad nearby roche moutonée. Active-source seismic tomography along seven profiles totaling ~2 km both extends borehole observations, mainly across strike. Several shears are scoured and backfilled with 15 meters of sediment or more. Finally, a comprehensive microgravity survey (1198 stations, ~30-meter station spacing) creates a site-wide map-view of shallow structure, illuminating both exposed and completely buried NE-trending shears. Our combined approach shows that glaciers separately stalled atop two ENE-trending (valley-crossing) antiforms at restraining left steps in the shear system, dropped a deceptively thin veneer of meter-scale erratics and impounded Homestake Creek, setting the stage for channel abandonment and two fen-like glacial meadows perched ~10 m above the modern thalweg. This study highlights some features of glacial/fault interaction and the utility of dense microgravity imaging in challenging structural settings.

Seismic Imaging Across the San Gregorio Fault Zone at Pescadero, California

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The right-lateral San Gregorio-Hosgri Fault (SGHF) is a major strand of the San Andreas fault system that forms the boundary between the Pacific and North American plates. The SGHF extends mainly offshore for approximately 400 km along the central California coast, merges with the San Andreas Fault at Bolinas, California to the north, and terminates at the western Transverse Ranges near Point Arguello to the south. Prior studies provide highly variable estimates of slip, which indicates uncertainty about the seismic hazard associated with the SGHF. To better understand the structure and geometry of the Frijoles Fault strand of SGHF, we conducted a 585-m-long, active-source, high-resolution (5-m shot and receiver spacing) seismic imaging survey across the fault where it is onshore at Pescadero, California. We recorded both P- and S-wave seismic data along the linear profile and used 2-D refraction tomography to develop V_P, V_S, V_P/V_S, and Poisson's ratio tomographic models. Additionally, we used the Multichannel Analysis of Surface Waves (MASW) method to develop a second V_S model. Our V_P model, with maximum velocities of 4200 m/s at 60 m depth, shows a prominent low-velocity zone with velocities between 2600 and 2800 m/s west of the mapped surface trace of the fault. We also observe a small increase in the depth of the 1500 m/s V_P contour (groundwater) slightly west of the near-surface trace of the fault, suggesting the fault acts as a groundwater barrier. Our V_S models show velocities range from about 120 to 500 m/s in the upper 30 m, with a lower velocity west of the surface trace of the fault. Based on our V_P and V_S models, we interpret a west-dipping main fault and possibly a minor splay approximately 100 to 150 m to the east of the main surface fault trace. This faulting geometry suggest a component of down-to-the-west normal faulting associated with the dominantly strike-slip San Gregorio fault.

Structure and Geometry of an Exposed Active Subduction Zone Splay Fault: The Deception Creek Strand of the Patton Bay Fault, Montague Island, Alaska

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In the 1964 Mw 9.2 subduction megathrust earthquake, the Patton Bay Fault (PBF) on Montague Island, Alaska, exhibited clear evidence of surface rupture and up to 10 meters of vertical displacement. The PBF offers a unique opportunity to investigate the internal structure of a rapidly-exhuming onshore exposure of an active brittle splay fault. The PBF can be traced 35 km along Montague Island and likely continues 70+ km offshore. On SW Montague Island, the fault exposure branches into two strands which exhibit different displacement histories. The Strike Creek strand ruptured in 1964, whereas the Deception Creek strand did not, but the latter lies at the base of the main topographic break of the island, indicating large net reverse displacement over many earthquake cycles. We investigated the structure of these strands using field observations, drone-based imaging and analysis of fault- and wall-rock samples. Apatite fission-track and detrital-zircon data support a common exhumation history across bedrock exposures of both the Strike Creek and Deception Creek fault strands. Beach platform outcrops of the Deception Creek strand reveal a ~150 m wide fault zone consisting of an incohesive gouge fault core and a bounding highly fractured damage zone hosted in sandstone and siltstone turbidites. Using structure-from-motion methods we created an orthomosaic of the fault zone on the uplifted beach platform and mapped the width and extent of the gouge-dominated fault core. The fault core is an ~5 m wide zone of incohesive gouge; splays of mm-scale localized slip surfaces with subsidiary gouge zones extend it an additional 5 meters into damage zone. The damage zone transitions over ~50-100 m from highly fractured rock with lenses of disrupted bedding to macroscopically unaltered wall-rock. Quantifying the thickness of the fault zone and its structural features permits us to compare observations from offshore geophysical imaging to this and other splay faults.

Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors

Oral Session · Thursday 21 April · 10:00 AM Pacific

Conveners: Verónica Rodríguez Tribaldos, Lawrence Berkeley National Laboratory (vrodrigueztribaldos@lbl.gov); Kirsten Chojnicki, Pacific Northwest National Laboratory (kirsten.chojnicki@pnnl.gov); Ariel Lellouch, Tel Aviv University (ariellel@mail.tau.ac.il); Hunter A. Knox, Pacific Northwest National Laboratory (hunter.knox@pnnl.gov); Patrick Paitz, ETH Zurich (patrick.paitz@erdw.ethz.ch); Brad Lipovsky, University of Washington (bpl7@uw.edu); Herb Wang, University of Wisconsin (hfwang@wisc.edu)

An Examination of DAS as a Possible Earthquake Early Warning Tool

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Distributed acoustic sensing (DAS) possesses potential for increasing the effectiveness of earthquake early warning (EEW), especially for offshore events. DAS data provide measurements of strain or strain-rate as a function of time and unlike station-based data, which are recorded at discrete locations, DAS data include recordings at high spatial density (~2 to 10 m channel spacing) along lines or in boreholes. DAS possess significant advantages for EEW such as low cost and dense deployments in previously challenging environments, such as offshore or in urban areas, but also has disadvantages such as constraints on the dynamic range and large data volumes. Here, we investigate the potential of DAS using data from two datasets: 1) strong ground motions recorded 80 m from a buried explosion and 2) an M 5.3 earthquake (5 June 2021 Calipatria, CA) recorded by 27 km dark fiber deployment in the Imperial Valley with the closest channel locations approximately 12 km from the earthquake epicenter. Currently, EEW detection schemes require: 1) seismic information to identify when large ground motions are underway, typically requiring estimates of the earthquake magnitude and epicenter; 2) determining if these detected ground motions are significant enough to issue an EEW alert; and 3) alerts issued in a timely fashion, usually prior to the S-wave arrival that carries the largest amplitude waves. We explore the potential use of DAS for each of these factors to provide information for both source-based (earthquake magnitude and epicenter estimates required) and ground-motion based (only estimates of location of large ground motions required) EEW methods.

Seismicity Monitoring Using Sub-array Processing of Large-aperture DAS Arrays

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Using unused or "dark" fibers from a 100 kilometer long segment of existing fiber-optic telecommunications cable near Mammoth Lakes, California, we recorded earthquakes using a DAS (Distributed Acoustic Sensing) interrogator. The fine channel spacing of 10 meters gives 10,000 recorded channels, sampling earthquake wavefields very densely and offering a variety of opportunities for multi-channel data processing and analysis. Using an existing fiber allows for rapid deployment with low effort in a seismically active area like Mammoth Lakes or to record aftershocks from a large event. During a ten-hour recording period, we recorded eight earthquakes captured in the USGS catalog from as far away as southern Nevada, with magnitudes ranging from 0.8 to 2.6. We also recorded over a dozen weak local events, not captured by the surrounding seismic network, with estimated magnitudes down to -1.3. DAS records a single component (the projection of the strain wave field onto the fiber), so conventional location and magnitude estimation algorithms need adjustment. The large number of channels and fine channel spacing helps us to define sub-arrays with optimal SNR for processing, detection and event mapping purposes. We mapped event locations using a grid-search approach and estimated local magnitudes. For events in the USGS catalog, we compare locations and magnitudes and discuss possibilities for joint analysis of geophone and DAS data.

Seismic Monitoring Using Dark Fiber and Distributed Acoustic Sensing (DAS) in the Imperial Valley, California

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We present results from a dark fiber distributed acoustic sensing (DAS) experiment conducted in the Imperial Valley, California. The DAS technique continuously transmits pulses of light through the fiber optic cables which naturally interact with imperfections within the fiber, thereby backscattering some of the light. This backscattered light can be measured by an interrogator unit which converts the data to strain, or strain rate, in the direction of the fiber. Using this data source, we identify and map local events recorded on the fiber using both traditional STA/LTA routines and two different types of template matching techniques. We are able to successfully detect known catalog events and new events not originally in the SCEC catalog, using both the traditional STA/LTA techniques and template-matching techniques. Identification of new events with a template-matching technique has the added benefit of allowing for an initial event location based on the location of the template event. The overall aim of this investigation is to help transform fiber data into products useful for basin-scale geothermal system characterization and subsurface mapping.

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Back-projection Imaging of the 2021 Antelope Valley m6.0 Earthquake Using Distributed Acoustic Sensing

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Back-projection of high-frequency teleseismic P waves improves our understanding of the temporal and spatial rupture evolution of large earthquakes. Yet, its application to moderate-sized earthquakes is limited due to the lack of dense local seismic arrays and complicated raypath caused by heterogeneous crustal structures. Here, we push the resolution limit of back-projection for moderate-sized earthquakes by converting two pre-existing dark fibers into an ultra-dense seismic array. With about 9,000 channels spanning a total distance of around 90 kilometers, we applied a 3D back-projection imaging and tracked the high-resolution rupture process for the July 8th, Mw6.0 earthquake in the Antelope Valley, eastern California. We resolved four high-frequency energetic subevents in a 3 km-by-5 km spatial dimension and a 5-second window following the initial break. We verified their location and origin time by timing their S-wave arrival on several nearby strong-motion stations. By comparing with the source time function determined from long-period waveforms, we found their timings mark the onset of high moment release. We suggest that the high-frequency subevents could be related to the initiation/breaking of individual rupture asperities. With more fiber-optic cables converted into seismic antennas, ruptures of moderate-size earthquakes can be systematically imaged in great detail on regional scales.

Phase Picking on Distributed Acoustic Sensing Data Using Semi-supervised Learning

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Distributed Acoustic Sensing (DAS) is an emerging technology for earthquake monitoring and subsurface imaging. However, the recorded seismic signals by DAS have several distinct characteristics such as unknown coupling effects, strong anthropogenic noise and ultra-dense spatial sampling. These aspects differ from conventional seismic data recorded by seismic networks, making it challenging to utilize DAS at the present for seismic monitoring. New data analysis algorithms are needed to extract useful information from DAS data, such as determining the first arrival times of P- and S-phases for earthquake monitoring and tomography. Previous research on conventional seismic data has demonstrated that deep learning models can achieve performance close to human analysts in picking P- and S-phases after training on manual labels. However, phase picking on DAS data is still a difficult problem due to the lack of manual labels. Further, the differences in mathematical structure between these two data formats, i.e., ultra-dense DAS arrays and sparse seismic networks, makes finning-turing of pre-trained models or transfer learning difficult to implement on DAS. In this work, we propose a new approach using semi-supervised learning to solve the phase picking task on DAS arrays. We use a pre-trained PhaseNet model as a teacher network to generate noisy P- and S-labels on DAS data and apply simple filtering to clean up these noisy labels to build training datasets. We develop a new deep learning model, PhaseNet-DAS, to process the 2D spatial-temporal data of DAS arrays and train the model using the Ridgerest DAS array deployed during the 2019 Ridgecrest earthquake sequence. The new deep learning model achieves a high picking accuracy and good earthquake detections performance on DAS data. Our approach using semi-supervised learning provides a new way to apply current deep learning models trained on seismometers to building effective deep learning models for DAS arrays.

Taiwan Milun Fault Drilling and All-inclusive Sensing (MiDAS) Project: Downhole Optical Fiber Through Frequent Slip Active Fault Zone

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The Milun fault Drilling and All-inclusive Sensing (MiDAS) project carries out a drilling into a recent ruptured active fault and setup a cross-fault zone observatory at depth. The goal of this project, despite the scientific challenges in understanding earthquake dynamics, is also to map seismogenic structure and stress state around the junction of collision to subduction zones, which has potential to the generation of M8+ subduction zone earthquake. The exciting experiment on MiDAS project is the installation of a crossing-fault vertical optical fiber with Distributed Acoustic Sensing, DAS/ Distributed Temperature Sensing, DTS system for seismicity and temperature monitoring. The drilling plan is to drill a 700m deep hole at the eastern side of Milun fault, which ruptured in 20180206 M6.4 Hualien, and 19511022 M7.3 Hualien earthquakes. We successfully retrieved the fault gouge at depth with coring from 360-520m, along with logging and successful downhole optical fiber installation through the fault zone on 31/12/2021. In the beginning of 2022, MiDAS_OFiber had successfully capture the signal associated with a subduction zone interface event and also some moderate size crustal events. Although more comprehensive studies are needed, the first look of the records through iDAS shows very local amplification of the strain-rate at depth. Another 500m hole will be drilled in early 2022 at the western side of fault with also optical fiber to build a 3D configuration of the monitoring system. The long-term observatory will also include the vertical seismic array (full band and short period). Together with the DTS on optical fiber for temperature monitoring, we hope to have chance to capture the friction heat of future near-by earthquakes for earthquake energy budget investigation. The MiDAS project for its special geographical location, we hope it will provide new and key observations for earthquake nucleation, energy budget and state of the stress toward our understanding of earthquake dynamics.

High-resolution Eikonal Traveltime Tomography of the Long Valley Caldera Using Distributed Acoustic Sensing

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The ability to image fine-scale subsurface structures present within a volcanic complex can provide crucial insights into the fundamental mechanisms driving magmatic systems. For instance, high-resolution and accurate velocity models would better characterize the long-period seismicity, commonly occurring within volcanic areas and highlight the complexity of the plumbing system connecting a caldera to the surface geological structures. However, the typical kilometric spatial sampling of seismic arrays over volcanoes makes it challenging to achieve the necessary resolution. The usage of existing telecommunication fibers by distributed acoustic sensing (DAS) enables the efficient deployment of seismic recording systems with meters channel spacing and tenths-of-kilometers range, thus may be ideal for the seismic tomography of volcanoes.

In this study, we deployed two DAS interrogator units in the Long Valley caldera area in eastern California with a combined fiber length of more than 90 km. Using the USGS earthquake catalog, we identify multiple events recorded by our systems for more than a year. By employing a machine-learning algorithm, we accurately pick the P- and S-wave arrivals of events with a good signal-noise ratio. The traveltime picks are then inverted using a novel matrix-free Eikonal tomography methodology that can correctly resolve subsurface structures with dimensions between 5 and 10 km. By applying this tomographic technique to the recorded DAS data, we obtain P- and S-wave velocity models that highlight the complexity of the structures composing this volcanic system, which can lead to a better understanding of its geological processes.

Subsurface Imaging of Distributed Acoustic Sensing Data Using a Dark Fiber Line in Reno, Nevada

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Application of Distributed Acoustic Sensing (DAS) strain rate measurements of the ambient noise data has recently been studied in various areas of seismic imaging at the local and global scales. DAS measurement using a dark fiber line is particularly of interest due to the vast existing infrastructure of fiber optic networks used for telecommunication. In theory, the entire fiber-optic network may be used as a seismic acquisition instrument to measure broadband ground motion, allowing imaging of the underlying site conditions in places that would otherwise be too costly or impossible to perform with nodal seismic acquisition systems. One of the challenges faced in the imaging of the underlying site conditions using a dark fiber line in urban environments is the high level of anthropogenic noise sources and its proximity to the fiber line. The materials used in burying the fiber optic cable and its coupling with the surrounding soil can vary from one location to another due to its original application as a telecommunication instrument. These conditions add additional uncertainties in the usefulness of dark fiber DAS data in subsurface imaging of urban environments, which requires further analyses. The purpose of the current study is to analyze the usefulness of the obtained strain rate measurements using the dark fiber line in acquiring the dispersion curve and its inversion. The results show a good recovery of the dispersion curve fundamental mode from the noise correlation function acquired from DAS measurements. Performing a global 1D inversion of the acquired dispersion curve reveals variations in the layering structure of the underlying soil material. The inversion of the obtained dispersion curve can be used in improving understanding of the ground motion due to earthquakes in urban environments or be used as an initial model for more detailed imaging of the subsurface using a full waveform inversion method.

Monitoring Ocean Surface Waves Offshore the Oregon Coast With Distributed Acoustic Sensing

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Ocean-bottom Distributed Acoustic Sensing (OBDAS) is a new technique to measure ground strain along fiber-optic cables with a very dense spatial spacing. This technology provides an unprecedented way to detect and monitor physical phenomena happening offshore, where seismometers are generally scarce. In this study, we analyze four months of continuous data recorded by a telecommunication cable deployed offshore the coast of Oregon, USA. The data were recorded along the first 60 km of the fiber between August and December 2021 with a Febus A1R interrogator. The gauge length was set to 40 m, the channel spacing to 20 m and the sampling rate to 100 Hz. We first analyze the frequency content of the recorded signals along the fiber-optic cable. At low frequency (< 0.2 Hz), we observe the signature of ocean surface waves up to 50 kilometers from the coast. We then compute Cross-Correlation Functions (CCFs) every 20-min between channels spaced by a few hundreds of meters along the cable. In the 5 to 50 s period range, the CCFs are dominated by clear dispersive waves propagating with a velocity of ~20 m/s, which is characteristic of ocean surface waves. We monitor the propagation of these waves along the cable using the relative velocity change method (dv/v). We detect clear temporal and spatial velocity changes of the ocean surface waves with values up to 10% of their average velocity. We finally use buoy and meteorological data recorded near the fiber-optic cable to gain a better understanding of our results. This study shows that OBDAS can be used to monitor phenomena happening inside the water column and could also be a powerful tool for oceanographers.

DAS Can Record Storm-induced Seismic Signals in Urban Areas

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Natural hazard events (windstorms and floods) could threaten life and property in populated areas. Estimating the disaster level in different parts of the affected zone will facilitate timely and precise warning and benefit risk management. Currently only limited meteorological monitoring stations are available in cities. Recent studies have shown that seismometers are sensitive to noise induced by wind and rain. Distributed acoustic sensing (DAS) could turn existing optic fibers into dense seismic arrays in cities and can serve real-time sensors to detect vibrations at the meter scale over the long distance. The goal of this study is to search for and characterize the storm-induced seismic signals in DAS recordings in urban areas.

Here, we analyze 2-month DAS recordings from Penn State FORESEE array and identify numerous weather-induced signals across 4-km-long fiber path from July to September, 2021. These events agree with meteorological data (wind speed and rainfall) recorded by nearby weather stations. Further data analysis shows that surface objects (light poles and trees) swaying in the wind could generate seismic noise in low frequency band (0.5-10 Hz). The energy decay fast while propagating and we develop an inversion algorithm to determine attenuation factor of shallow subsurface (~ 1 m). The correlation between seismic energy and wind speed observations can be observed around the natural frequency of vibrating objects. We also show that raindrops hit the concrete ground and generate strong noise in the frequency band of 20-120 Hz. Moreover, channels near the drainage system also record low frequency noise (1-10 Hz) possibly caused by water flowing in the sewer. These findings show the possibility of extracting quantitative wind speed and precipitation estimates from DAS arrays.

Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors

Poster Session · Thursday 21 April · Conveners: Verónica Rodríguez Tribaldos, Lawrence Berkeley National Laboratory (vrodrigueztribaldos@lbl.gov); Kirsten Chojnicki, Pacific Northwest National Laboratory (kirsten.chojnicki@pnnl.gov); Ariel Lellouch, Tel Aviv University (ariellel@mail.tau.ac.il); Hunter A. Knox, Pacific Northwest National Laboratory (hunter.knox@pnnl.gov); Patrick Paitz, ETH Zurich (patrick.paitz@erdw.ethz.ch); Brad Lipovsky, University of Washington (bpl7@uw.edu); Herb Wang, University of Wisconsin (hfwang@wisc.edu)

A Comparison of Approaches To Convert DAS Measurements to Ground Motion

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Distributed Acoustic Sensing (DAS), as applied in seismological investigations, measures ground motion as strain or strain-rate averaged over an interval, called the gauge length, along a cable. Traditional seismic measurements are sensitive to ground motion (e.g., velocity or acceleration) at a point rather than a spatially distributed sensitivity. To use DAS data for deriving measurements like earthquake magnitude and explosion yield estimates, using algorithms formulated for traditional ground motion measurements as inputs, it is advantageous to convert strain-based measurements into velocities or accelerations. The theoretical relationship between strain-rate and acceleration, and strain and velocity is well established and has been successfully used to convert DAS measurements in several instances, as strain-rate is proportional to acceleration and strain is proportional to velocity, where the proportionality constant is phase velocity. Strain-rate can also be derived from the spatial derivative of velocity in the direction of the fiber axis. These relationships have been used to derive several algorithms for converting DAS measurements to ground motions including spatial integration, scaling in the f-k domain and

measuring moveout velocities for individual phases. While successful conversions of DAS data have been reported in the literature, difficulties have been noted in certain conditions. For example, the f-k approach can produce undesirable low-wavenumber noise, and moveout velocities derived from direct arrivals will not scale later phases correctly. Here we explore how conditions, such as geologic setting and proximity to an explosive source, may complicate relating DAS and traditional seismic measurements by comparing the performance of some of these approaches on synthetic and real DAS data.

Combining Dark Fiber and Seismic Interferometry to Measure Physical Properties of an Earthquake Swarm

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Fiber optic sensors enable dense (meter-scale) sampling of the seismic wavefield over large distances (10's of km). When an earthquake is recorded by such an array, we see detailed ground motion, including highly scattered arrivals caused by heterogeneities along the entire path between the source and each channel along the length of the fiber. Given two earthquakes along similar paths, we can use interferometry to isolate the part of the wavefield between them. This results in a estimate of the Green function between the pair, modified by the two moment tensors. Given a swarm of events, we can measure the physical properties of the tectonically active zone, including source properties and geologic structures.

Here, we present results from the Imperial Valley dark fiber experiment, which recorded hundreds of local earthquakes during its deployment, including a large swarm near the southern end of the Salton Sea. We illustrate the methodology and the sensitivity of the technique with respect to earthquake magnitude, distance and relative geometries and contrast the application of dense DAS fiber with more traditional seismic arrays.

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De-noising DAS Data Using an Adaptive Frequency-wavenumber Filter

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Data recorded by distributed acoustic sensing (DAS) along an optical fiber sample the spatial and temporal properties of seismic wavefields at highest density and often lead to massive data when collected for seismic monitoring along kilometer long cables. Coherent signals from weak seismic arrivals within the data are often obscured by incoherent noise. We present a flexible and extremely efficient filtering technique which handles the large amount of data and makes use of its dense spatial and temporal sampling. The applied adaptive frequency-wavenumber filter suppresses the incoherent seismic noise while emphasizing the coherent wave field. We investigate the implementation of the modified Goldstein filter and analyse the response of the filter in time and spectral domain. The filters' performance is demonstrated on a noisy data set recorded in a vertical borehole showing active and passive seismic phase arrivals. Lastly we present a highly performant software implementation enabling real-time filtering of large DAS data sets.

Directional Sensitivity of DAS and Its Effect on Rayleigh Wave Tomography

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Distributed acoustic sensing (DAS) provides dense arrays ideal for seismic tomography. However, DAS only records average longitudinal strain change, which can complicate the interpretation of surface wave observations. Commonly, DAS surface wave tomography is performed considering channels in a radial-radial alignment, such that the resulting cross-correlations merely have surface waves of the Rayleigh type. In this scenario, only the subsurface exactly beneath a straight line can be imaged.

With a rectangular DAS array located in Oxnard, California, we conducted a pilot study to examine the directional sensitivity of DAS measurements and the feasibility of recovering subsurface structures within the array geometry. We compare the phase velocity dispersion of the same locations illuminated by different virtual sources, and the dispersion curves show excellent consistency for collinear and non-collinear virtual sources. This result suggests that surface wave observations in most of the cross-correlations are dominated by Rayleigh waves.

Based on the above assumption, we extract Rayleigh wave signals through ambient noise cross-correlations and our measurements of the amplitude confirm the theoretical directional sensitivity of DAS. For cross-correlations of non-collinear channel pairs, the travel time of each connecting raypath can still be obtained despite the lower signal-noise ratio (SNR) of Rayleigh wave signals. We then invert for a Rayleigh wave dispersion map and eventually a subsurface shear velocity model. The resolved velocity model reveals an ancient river channel consistent with the local geologic map. The results demonstrate the prospect of 3D surface wave tomography with DAS arrays of complex geometry.

High-resolution Ambient Seismic Noise Monitoring of Geothermal Systems in California's Imperial Valley Using Dark Fiber Distributed Acoustic Sensing (DAS)

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Detailed characterization and monitoring of geothermal systems for efficient and safe exploitation remains a challenge, mostly due to difficulty of acquiring long-term, high-resolution geophysical datasets at the regional scale. Tracking spatio-temporal changes in relative seismic velocities (dv/v) has emerged as an attractive tool for monitoring subsurface processes. Current approaches use sparsely distributed (several km) seismic stations and exploit weak, natural ambient seismic noise that can only yield monthly or seasonal changes. Distributed Acoustic Sensing (DAS) could become an ideal alternative, providing large aperture arrays (10s of km), dense spatial sampling (~ 1 m) and broad frequency response (mHz to kHz).

We explore the use of DAS deployed on unused telecommunication fiber-optic cables (dark fibers) for monitoring short-term (daily) and long-term velocity perturbations associated with shallow hydrological systems and deeper processes related to geothermal reservoirs. Coda wave interferometry techniques are applied to eight months of continuous ambient seismic noise data recorded along a 27 km-long dark fiber array located in Imperial Valley, Imperial County, CA, which contains productive and hidden geothermal systems. The profile traverses the northern portion of the valley between Calipatria and Imperial, crossing tectonically active areas and the eastern margin of the Brawley geothermal field. In this study, one km-long subarrays are analyzed following a roll-along approach to retrieve dv/v observations every few hundred meters. To mitigate the processing challenges associated to the large datasets generated by long-term, regional DAS studies, we utilize DASSA, a new processing framework that enables scalable, parallel analysis of DAS ambient noise data on modern supercomputers. This study illustrates the potential of dark fiber DAS to become a tool for efficient, continuous monitoring of subsurface changes relevant to geothermal systems.

Initial Steps Towards a DAS Metadata Model

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The number of Distributed Acoustic Sensing (DAS) research datasets is increasing rapidly and cover a range of applications, from ice movement to subsurface monitoring to earthquake hazard. As the number of available interrogators increases, it is expected that the need for archiving of the datasets will also increase. Long term archiving faces two main challenges at present: the

need for large amounts (100's TB) of storage and a standardized metadata format. As part of the DAS Research Coordination Network (RCN), a DAS data management working group is constructing a metadata model for DAS data. The objective is to develop a common metadata standard for archival purposes and to guide data collection at experiments. The metadata requirements include: 1) accommodation of most use cases (data collection scenarios); 2) permitting of cloud-based processing; 3) allowing of pre-processing and 4) reduction of the burden of data transport. We propose to divide the metadata into distinct groups consisting of overview (basic information about the experiment), acquisition (type of interrogator and acquisition parameters) and cable and fiber descriptions. A subset will be denoted as "required" metadata and standard metadata principles, such as findability, accessibility, interoperability, reusability (FAIR) and machine-readability, will be adhered to. The purpose of this presentation is to inform potential users of these efforts, encourage adoption of the proposed standard and invite community input.

Local Earthquake Detectability Using Long-haul Fiber Cables With DAS Technology

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Over the past decades, distributed acoustic sensing (DAS) has been at the forefront of seismology due to density of sensors. However, due to limitations of the available fiber cables, each DAS array has different sensitivities to ground motion. In summer 2021, we connected a Silixa iDAS interrogator to two long-haul fiber segments (50 km and 66 km, respectively) in Enid, Oklahoma using the first 20 km of each segment. The DAS array is located along a state highway and has pockets of high noise, such as on/off ramps.

In this study, we use 47 local earthquakes from the OGS catalog that located are within 30 km of the DAS arrays to examine the relationship between detectability on DAS array and event information.

Initial waveform inspection shows that local traffic signal is mostly above 10 Hz, while local earthquakes have broader frequency range. For each earthquake, we compute RMS (root-mean-square) for each trace before and after low pass filter below 8 Hz and then visually scan the waveform and RMS images. As a result, we identify 27 out of the 47 events on the DAS array. Among the 27 events, 11 are visually observable without filter due to their proximity to the array, while the other events require filtering to be separated from local traffic.

These 47 events are distributed within 8 separate spatial clusters according to the OGS catalog. Our next step is to apply automatic picking algorithm to extract windowed waveforms for the 27 events that are visually detected on DAS array, then use them as templates to scan through continuous waveform via waveform cross-correlation and stacking to detect other events in each cluster.

We will further analyze the relationship between signal quality and energy on the DAS array and event source information (i.e., magnitude, distance, azimuth, focal mechanism). We will also compare the signal between the DAS array and collocated nodal arrays for selected events. These efforts are expected to better understand the sensitivity and detectability of the DAS array along a noisy state highway.

Reno, Nevada Dark Fiber DAS Experiment: Frequency Response Among Various Seismic Instruments

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Distributed acoustic sensing (DAS) gives seismologists and engineers a relatively new and advantageous way to monitor earthquakes and other seismic signals with spatially dense measurements, notably as dark fiber in urban environments where monitoring and seismic hazard assessment are important. However, the ability to use dark fiber in these urban environments to determine the subsurface structure and source characterization of earthquakes has not yet been fully established; additionally, using dark fiber for DAS in urban areas depends on the configuration and materials in which the cable was buried, so it differs between experiments and locations within an experiment. We conducted a dark fiber DAS experiment in 2021 from August 27th to October 1st, mainly within the downtown city center of Reno, Nevada. We measured and analyzed ~12 km of dark fiber. We installed 27 temporary nodal seismometers at various locations along the cable and gathered data from a permanently installed seismometer run by the Nevada Seismological Laboratory. We aim to compare the dark fiber DAS data with nodal and traditional seismometer data to improve seismic hazard analysis in an urban environment and determine if we can accurately characterize earthquake source properties. We were able to detect several local and teleseismic events. We chose to analyze two small local events (M 3.2 and M 2.5) and an M 7.4 Mexico event. We present preliminary results comparing the frequency response among the different instruments.

Towards Inversion of the Microseismic Moment Tensor With DAS: Application to Boreholes

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We present preliminary results on a workflow for moment tensor inversion with Distributed Acoustic Sensing (DAS) data. It makes use of a fast-marching Eikonal solver and synthetically modeled data. This study focuses on borehole settings for geothermal sites, specifically in the Utah FORGE geothermal test site. The DAS measurement captures the wavefield with high spatial and temporal resolution. On the one hand, in borehole settings, individual DAS traces generally prove to be noisier than co-located geophones. On the other hand, the densely spaced DAS shot-gathers show features that would have otherwise been missed by the commonly more sparsely distributed geophone chains. The high coherency and detail in DAS data can therefore help to constrain the moment tensor of the microseismic source. The synthetic tests focus on different source types and positions relative to the deployed fiber to assess the resolvability of the moment tensor. Further tests include the addition of a three-component seismometer at different positions to investigate an optimal network configuration, as well as various noise conditions to mimic real data. The synthetic tests are done as preparation for data from future microseismicity monitoring in enhanced geothermal projects as part of the EU-funded DEEP project (De-risking Enhanced geothermal Energy Projects). The proposed method aims at improving amplitude-based moment tensor inversion for DAS deployed in downhole or underground lab contexts.

From Desktops to HPC & Cloud: Emerging Strategies in Large-scale Geophysical Data Analysis

Poster Session · Wednesday 20 April · Conveners: Chad Trabant, Incorporated Research Institutions for Seismology (chad.trabant@iris.edu); Jonathan K. MacCarthy, Los Alamos National Laboratory (jkmacc@lanl.gov)

Efficient Access and Manipulation of Big Seismic Data from Disparate Sources

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Seismological data recordings have been growing exponentially in the last three decades. For instance, the data archive at the IRIS Data Management Center (DMC) grew from less than 10 Tebibytes in 1992 to greater than 750 Tebibytes today (in 2022). In addition to such big data archives, retrieving and merging data from various disparate seismic sources also creates big data which will enable obtaining higher-resolution seismic images and understanding phenomena such as earthquake cycles. Moreover, recent progress in geosciences with the application of AI/ML using big data has shown the potential of discovering patterns that were not previously recognized. However, aggregating large seismic datasets introduces its own challenges. Some of these challenges arise from the fact that many data centers have their own way of distributing data, and the format of the data and metadata are different in many cases.

The objective of this investigation is the development of data access and manipulation tools for retrieval, merging, processing and the management of big seismic data from disparate seismic data sources. We develop a free, open-source, direct data accessing, gathering and processing software toolbox for disparate sources using Python. Aggregating data from different data centers will enable us to investigate the seismic structure beneath a region of interest at a higher resolution by merging the seismic databases. Such a merged dataset can be applied on studies around the boundaries between countries if those countries have different networks. One boundary region of geologic interest to exemplify the benefits of aggregated seismic datasets from different networks in two countries is the southern side of the Rio Grande Rift including the bordering areas between the US and Mexico. Previous more detailed seismic studies on Rio Grande were conducted mostly on the US side of the Rift Valley.

HDF5eis: A Solution for Storing and Accessing Big, Multidimensional Data From Environmental Sensors

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The seismological community's eager adoption of technologies such as large-N arrays, distributed acoustic sensing (DAS) and deep learning manifests a broader trend towards bigger data and bigger analyses in geoscience and beyond. This trend is forcing researchers to rethink the way we handle data as conventional formats and paradigms are stretched beyond their original design specifications. Fortunately geoscientists do not face this challenge alone; related communities have developed effective solutions for storing, accessing and processing big data sets, and domain-specific extensions of these have begun to emerge such as the Adaptable Seismic Data Format and PASSCAL HDF5 extensions of the superb HDF5 library and file format.

Recognizing storage of and access to big data as an ongoing challenge with evolving use cases, we present HDF5eis (read H-D-F-Size): A prototypical, HDF5-based file format designed for high-performance storage of and access to big, multidimensional data from environmental sensors. We present HDF5eis not as a final, one-size-fits-all solution, but rather with the intent of stimulating the ongoing conversation about which technologies to leverage and how to do so for solving problems related to big data in seismology and related fields. At the conference, we will discuss (a) differences between HDF5eis and existing, HDF5-based alternatives, (b) use cases and (c) plans for continued development.

Implementing Cloud-optimized Geophysical Data Containers

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UNAVCO Geodetic Data Services and IRIS Data Services are working together to migrate two independent self-managed data systems into a single cloud-based platform. As part of our migration and redesign work, we are implementing cloud-optimized data containers for a range of geophysical data types supported by our facilities. The primary goals of this effort are to support efficient data center operations and, importantly, to also allow direct access by researchers to stored data to support efficient processing. Initial work has been the development of several prototype data containers using TileDB's embedded storage engine. Early testing has demonstrated encouraging results for some of our more complex and important use cases. Our objective is to leverage many of the attributes of TileDB arrays in our designs, including: multiple-dimensional slicing, compression filters, parallel IO, cloud storage backends, support for sparse arrays and versioning. The implementation of new geophysical containers will enable the development of a more diverse set of data queries across internal repositories, enabling improvements in our data discovery capabilities. In addition, researchers using data-proximate cloud resources will be able to take advantage of parallel access to our very large datasets, significantly reducing Extract, Transform and Load (ETL) timescales. An important objective satisfied by TileDB is interfaces to common programming languages (Python, R, C/C++, Java, Golang, C#) and frameworks (Xarray, Dask, Pandas) used by the research communities we support. We will report on the status of our development, challenges we've encountered and show some examples using our prototypes.

Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Andrea D. Hawkes, University of North Carolina Wilmington (hawkesa@uncw.edu); Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Lydia M. Staisch, U.S. Geological Survey (lstaisch@usgs.gov); SeanPaul La Selle, U.S. Geological Survey (slaselle@usgs.gov); Jason S. Padgett, University of Rhode Island (jason_padgett@uri.edu)

Influence of Subducting Rift Propagator Wakes on Cascadia Forearc Deformation and Earthquake Segmentation

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Mapping of JDF plate structure using both legacy and modern seismic reflection profiles suggests that significant upper plate structure in Cascadia may be associated with rift propagator wakes (RPW) originally mapped by Wilson (1988, 2002). These features were mapped with magnetic anomalies primarily, with some support from reflection profiles, and form as a result of one ridge segment growing at the expense of another, leaving a "wake". The recent compilation shows that the RPW are more extensive than previously realized, both in lateral extent and in topographic expression. The surface expression, mapped as basement topography in the subsurface, includes not only tall seamounts, but deep holes as deep as 2.0 seconds TWT, or about 1800m. While a typical expression includes vertical features of 300-500m, in some cases as much as 1600m of basement topography is observed. RPW are also broad, typically ~ 80-100 km wide, but up to 120km. Seamounts are associated with the RPW, not by numbers, but by size and volume. While the recently subducted segments of the RPW are not observed directly, new structural mapping in Cascadia reveals deformation of the accretionary prism associated with subducting RPW and their associated seamounts. Two major submarine structural uplifts, Heceta and Nehalem Banks, have long term deformation that includes significant post-Miocene shorting and uplift. Their existence has not been previously determined, but they appear to be associated with the subducting RPW, with have moved slowly southward relative to the forearc. Previous positions of the RPW in the mid-Miocene may have been responsible for initiation of extensive normal faulting off Washington. The modern positions of the RPW may be consistent with paleoseismic segmentation proposed using onshore and offshore paleoseismic data. The RPW may act as either weak or strong members within the subducting plate. Published gravity models exist for both scenarios, while reflection data support a broad subcrustal underplating of oceanic crust and higher seismic velocities, supporting a strong member scenario.

Upper Plate Structure and Tsunamigenic Faults Near the Kodiak Islands, Alaska

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The Kodiak Islands lie near the southern terminus of the 1964 Great Alaska earthquake rupture area and within the Kodiak subduction zone segment. Both local and trans-Pacific tsunamis were generated during this devastating megathrust event, but the local tsunami source region and the causative faults are poorly understood. We provide an updated view of the tsunami and earthquake hazard for the Kodiak Islands region by combining historic earthquake and tsunami information with new tsunami modelling and geophysical data analysis. Of particular interest are two offshore fault zones, the Kodiak Shelf and Albatross Banks fault zones. Through seismic and bathymetric data, we characterize a regionally extensive sea floor lineament related to the Kodiak shelf fault zone, with focused uplift along a 50-km long portion of the newly named Ugak fault as the most likely source of the local Kodiak Islands tsunami in 1964. We present evidence of Holocene motion along the Albatross Banks fault zone, but suggest that this fault did not produce a tsunami in 1964. We relate major structural boundaries to active forearc splay faults, where tectonic uplift is collocated with gravity lineations. Differences in interseismic locking, seismicity-rates, and potential field signatures argue for different conditions at depth near presumed segment boundaries. We find that the Kodiak segment boundaries have a clear geophysical expression and are linked to upper plate structure and splay faulting. The tsunamigenic fault hazard is higher for the Kodiak shelf fault zone when compared to the nearby Albatross Banks fault zone, suggesting short travel paths and little tsunami warning time for nearby communities.

Evaluating Rupture Models of the 1700 CE Tsunami With Detailed Mapping of Tsunami Deposits and Sediment Transport Modeling

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The last great earthquake on the Cascadia subduction zone (1700 CE) ruptured much of the plate boundary and generated a high tsunami that deposited sand in coastal marshes from Vancouver Island to northern California. Although the geologic record of tsunami inundation is extensive in some of these marshes, few sites have been cored enough to accurately determine the inland limit of sand deposition and capture the variability in tsunami deposit thickness. At the Salmon River Estuary, Oregon, we collected 105 cores and reanalyzed 114 core logs from a 1987-1988 study that delineates the inland extent (3.4 km from the river mouth) and thickness variation (0.1-19.5 cm) of sand deposited by the 1700 CE tsunami. These data were used to validate models of tsunami sediment transport (using Delft3D-FLOW), which was further used to test rupture models of the 1700 earthquake. Based on the 1700 deposit's inland extent, model results suggest that at least 15 m of megathrust slip occurred offshore of the Salmon River, a result that requires >1 m of coastal coseismic subsidence. This largely agrees with the updated microfossil paleogeodesy estimates of 1.3 ± 0.4 m of subsidence at the Salmon River in 1700. The inland extent of modeled tsunami deposition is sensitive to different inputs of surface roughness and river mouth topography. The model was run with a wide range of roughness values and adjusted topography, which ruled out earthquake sources with <1 m of subsidence as potential sources. Extensive mapping of tsunami deposits and sediment transport modeling at other coastal sites in Cascadia would help refine reconstructions of 1700 CE and older tsunamis. This methodology also provides constraints on estimates of coastal deformation during megathrust earthquakes, leading to improved earthquake and tsunami hazard assessments for Cascadia.

The 2021 South Sandwich Island Mw 8.2 Earthquake: A Slow Event Sandwiched Between Regular Ruptures

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The August 12, 2021, M_w 8.2 South Sandwich Island earthquake reveals surprising contrasts, because it was initially reported as a magnitude 7.5 event at a deep depth (47 km), but generated a ~400-km-long aftershock area and notable global-spreading tsunami, which would only be expected for a larger and shallower event. We determined the rupture process of this event, which appears to be a complex sequence both temporally and spatially. Given the complexity of this event, we applied a multiple subevent inversion on broadband seismograms from regional to global distances, to resolve its complex variations of fault geometry, location, depth and temporal characteristics. We found that the rupture initiated as a regular deep thrust earthquake; it then ruptured shallower and triggered a silently hidden and dominantly slow subevent extending ~200 km to the south and ended with 2 other regular subevents. The total duration is ~260s, unusually long for an M_w 8.2 event. Our result for this event is qualitatively consistent with its measured deviant m_B-M_w and M_S-M_w relations and other moment tensor solutions, yet further provides a more quantitative space-temporal pattern of this unusual sequence.

3D Acoustic-elastic Coupling with Gravity: The Dynamics of the 2018 Palu, Sulawesi Earthquake and Tsunami

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While tsunamis occur due to abrupt vertical perturbations to the water column, a devastating tsunami was caused by the strike-slip, supershear 2018, Palu, Sulawesi earthquake. Studying such surprising earthquake-tsunami behavior has been hampered by the necessity of making approximations in the fluid-solid coupling. Recent simulations (Ulrich et al., 2019) suggest that the Palu tsunami can be primarily understood from the complex interaction of transtensional earthquake rupture dynamics across a geometrically complex strike-slip fault system and the 3D bay bathymetry. However, the standard practice of linking a 3D earthquake simulation, conducted without a water layer, to a 2D tsunami shallow water model simplifies the interaction between the ocean floor and water column.

We develop a highly scalable 3D fully-coupled Earth and ocean model of earthquake rupture and tsunami generation implemented in SeisSol (Krenz et al., 2021). We model seismic, acoustic and surface gravity wave propagation sourced by physics-based non-linear earthquake dynamic rupture, naturally capturing tsunami dispersion and related nonhydrostatic effects during both tsunami generation and propagation. Multi-petascale simulations, with excellent performance on three different supercomputers, allow to include complicated geometries, such as high-resolution bathymetry, coastlines and segmented earthquake faults. We present the first fully coupled simulation of an actual earthquake-tsunami event and a 3D benchmark problem of tsunami generation by a megathrust dynamic earthquake rupture. There are notable differences in the fully coupled and 3D-2D linked models for the Palu event, potentially due to the non-hydrostatic ocean response and the complex, high-frequency source. Our work enables us to capture the entire dynamics of this process in an efficient, unified 3D model and our predictions of pressure changes in the water column, including at the seafloor, may help to interpret ocean bottom pressure sensor data containing more than just tsunami waves.

Frontiers in Earthquake and Tsunami Science—Model Integration, Recent Advances, Ongoing Questions

Poster Session · Friday 22 April · Conveners: Andrea D. Hawkes, University of North Carolina Wilmington (hawkesa@uncw.edu); Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Lydia M. Staisch, U.S. Geological Survey (lstaisch@usgs.gov); SeanPaul La Selle, U.S. Geological Survey (slaselle@usgs.gov); Jason S. Padgett, University of Rhode Island (jason_padgett@uri.edu)

A Comparison of Foraminifera and Diatom-based Transfer Function Estimates of Coseismic Subsidence During the 1700 CE Earthquake Along the Oregon Coast

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Comparison of microfossil assemblages (e.g., diatoms and foraminifera) in pre- and post-earthquake intertidal sediment is the most widely applicable and precise means to measure coseismic subsidence during past plate-boundary earthquakes at subduction zones in temperate regions. Coseismic subsidence estimates derived from transfer functions—which use the empirical relationship between modern microfossil assemblages and elevation within the tidal frame—are critical input to earthquake and tsunami source models, especially at subduction zones like Cascadia that lack historically recorded great megathrust earthquakes (M_w8+). However, differences in uncertainties on subsidence estimates between diatoms and foraminifera have not been fully explored. For example, ecological processes affect different microfossil groups in different ways, such as differing reproductive rates, sediment mixing, dissolution, limited supratidal and subtidal range. To evaluate the potential impact of these and other processes on coseismic subsidence estimates, we will compare foraminiferal- and diatom-based transfer function estimates of coseismic subsidence during the ~M9 1700 CE earthquake at a series of sites along the Oregon coast. We will develop a diatom-based Bayesian transfer function (BTF) using a new modern dataset of >150 diatom samples from transects spanning the supratidal to subtidal zones of tidal wetlands along the Oregon and northern California coasts. We will then test the performance of the BTF on a sediment contact recording a known increase in sea-level rise (equivalent to ~1m of coseismic subsidence, as might occur during a ~Mw 8-9 earthquake) from a dike removal during restoration of a former salt marsh along the Coquille River in southern Oregon. Finally, we will apply our diatom-based BTF to the 1700 CE earthquake contact at Oregon coastal sites with foraminiferal-based BTF subsidence estimates. These results will help in evaluating past and future diatom- and foraminiferal-based estimates of subsidence, and their uncertainties, during past megathrust earthquakes.

Diatom-based Quantification of Coseismic Land-level Change From Cascadia Subduction Zone Earthquakes in Southern Oregon

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Tidal wetlands along the Cascadia subduction zone (CSZ) record an extensive record of repeated land-level changes and tsunami inundation associated with great (>M8.0) earthquakes. Stratigraphic contacts consisting of peat sharply overlain by minerogenic tidal mud represent sudden coseismic subsidence of the coast. Broadscale environmental changes observed across sharp peat-mud contacts were first used to estimate the magnitude of coseismic subsidence, but often reported >1m uncertainty. More recent statistical methods of quantifying coseismic subsidence termed transfer functions have examined microfossils (e.g., foraminifera, diatoms) across peat-mud contacts, producing subsidence estimates with reported uncertainty as low as ±0.3m. These quantitative methods have been widely applied to the most recent CSZ event, dated to 1700 CE, and exposed along strike slip variability. However, there are limited quantitative coseismic subsidence estimates from older ruptures to compare slip heterogeneity though time. Along the southern Oregon coast, tidal wetlands preserve a ~7000-year history of CSZ ruptures but attempts to employ foraminifera-based transfer functions on contacts older than 1700 CE have been challenging due to poor foraminifera preservation. Diatoms, a single-celled algae composed of durable silicious valves may preserve better in those older contacts.

Here, we will apply diatom-based analysis across multiple peat-mud contacts preserved in cores from the Coquille River estuary in southern Oregon. We will develop and apply a diatom-based Bayesian transfer function, created from modern diatom datasets spanning the Oregon and Northern California coasts, to estimate the magnitude of subsidence during past earthquakes at the site. Our analysis will provide insights into the spatial and temporal variability of subsidence along the CSZ by providing the first quantitative subsidence estimates for pre 1700 CE earthquakes in southern Oregon.

Exploring Potential Causes for Observed Overprediction of Ground Shaking by USGS Hazard Maps Relative to Historical Shaking Data

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Probabilistic seismic hazard assessment (PSHA), which forecasts levels of earthquake shaking that should be exceeded with only a certain probability over a given period of time, is one of the most important products produced by the seismological community for earthquake risk mitigation. Seismologists have recently begun assessing how well PSHA models and corresponding maps forecast the shaking that actually occurs.

Salditch et al. (2020) found that current PSHA maps for California appear to overpredict shaking relative to the California Historical Intensity Mapping Project (CHIMP) dataset of the maximum observed shaking from the largest California earthquakes between 1857 and 2019. Qualitatively similar results have been obtained in Italy and Japan. We examine three possible causes for the overprediction in California: 1) site effects due to variations in V_{S30} (time-averaged shear-wave velocity in the top 30m of soil), which could amplify or deamplify ground motions relative to hazard maps for a reference site condition, 2) incompleteness of the CHIMP data set and 3) aleatory variability in conversion from peak ground acceleration (PGA) to Modified Mercalli Intensity (MMI). We find that incorporation of site-specific V_{S30} does not appreciably change maps and hence their inconsistency with CHIMP data, because at the short periods that control PGA (and MMI), nonlinear deamplification due to increased soil damping largely offsets linear amplification due to low V_{S30}. We show that the other two factors also cannot explain the discrepancy between predicted and observed shaking. We outline future work that will be undertaken to understand the discrepancy, with the goal of improving PSHA maps in California and, potentially, other regions. Remaining possible explanations include but are not limited to overestimation of aleatory variability in modern ground motion models, catalog limitations associated with a short historic record, and use of mean rather than median hazard to characterize PSHA.

Stochastic Tsunami Modeling Including Source Kinematics

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The influence of the kinematic part of the rupture often is neglected when tsunamis are modeled. Most of the time, passive generation is employed, which means that seafloor deformation is replicated into the sea surface. This is true under two assumptions: one is that the depth of the water is very small compared to the wavelength on the water surface and the rupture velocity is considered instantaneous compared to the tsunami velocity. Moreover, stochastic generation of seismic sources is a powerful tool to evaluate spatial uncertainties in seismic and tsunami assessment. Traditionally simplifications are commonly adopted such as static displacement avoiding the rupture propagation. The purpose in this study is to avoid these assumptions by including source kinematics, i.e, rupture velocity, moment rate function directivity, and rake variability. Application in the Kuril-Kamchatka trench shows a straightforward use of our methodology, producing simple hazard maps, which can be replicated in any region of the world.

The Cascadia Offshore Paleoseismic Record: A Visual Tour of the Systems Approach and Some Updates

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Turbidite paleoseismology offers challenges and opportunities to use a systems approach to deriving a paleoseismic history of an offshore fault system. Onshore, paleoseismology is done site by site, with only radiocarbon to link sites. Offshore, this can be done as well, but it's never possible to use radiocarbon to definitively test for synchroneity and therefore linkage of events. Offshore, sites can also be linked using other methods: 1) downcore stratigraphic series realizations [TSH1] using density, bed thickness, depositional structure and other parameters; 2) Individual bed structure ("fingerprinting") 3) Chirp sub-bottom tracing of individual beds; 4) testing for synchroneity using confluences and bed count, provenance mixing, tephras and other tracers; 5) comparisons between sites that can, and cannot receive non-seismically sourced turbidity currents; 6) sedimentologic tools to test for deep water sourcing; 7) comparisons to onshore paleoseismic records. In Cascadia, unlike most [TSH2] offshore settings, all of these tools are available, and are in use to approach the stratigraphic record from a systems perspective. One of the few tools unavailable is the testing of bed fingerprinting with known historic earthquakes as has been done in Sumatra and New Zealand. None of these tools, used alone, can definitively link an individual bed to an earthquake, but used together form a robust framework to test hypotheses. The Cascadia offshore Holocene record attempts to find a best-fitting model that can satisfy all the data. Testing of the model includes alternate realizations of the ages, assessment of convergence of the data, alternate flow paths, and alternate correlations. Recent work has included new cores, exploration of spatial sensitivities to paleoseismic/paleoclimate deposition, new age-depth models using high-resolution CT analysis, heavy-mineral provenance work, improved assessment of hemipelagic sedimentation rates, and analysis of historic events recorded in

Southern Cascadia. Overall, these analyses sustain support of the published 2012-2017 turbidite paleoseismic models.

Tsunami Generated From Asteroids Impacting Earth's Oceans: Consequences on Coastlines of USA for Disaster Response and Management Preparedness

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A hypothetical asteroid-impact scenario (https://cneos.jpl.nasa.gov/pd/cs/pdc21/) designed by the International Academy of Astronautics (IAA) is used as the basis for discussion and analyses of the table-top exercise. The asteroid is classified as a potentially hazardous asteroid with a diameter initially estimated between 35-700 meters. The asteroid's position uncertainty region at the time of the potential impact is much larger in both length and breadth than the size of the Earth. Impact could occur anywhere on the forward hemisphere during the hour or so when the Earth crosses the asteroid orbit and sweeps through the uncertainty region. Given the significant water-impact probability, and because most of the potentially affected coastal regions are heavily populated, we focused our simulation efforts on modeling water impacts at several locations along the asteroid risk corridor. We have simulated the problem from asteroid entry, to ocean impact, to wave/tsunami generation, propagation, interaction with the shoreline and the flooding of the coastline major cities. We have simulated four different asteroid diameters (100, 250, 500 and 700m) and we have delimited the zones of inundation for each scenario for risk assessment and disaster management & response around the world. Here we emphasis the coastlines of Latin America and the Caribbean. The interaction of the asteroid with the ocean are simulated using the hydrocode GEODYN, creating a wave source for the Boussinesq-based water-wave-propagation code, WWP. Run-up and flooding were simulated using WAST—water/structure—a CFD code for urban flooding assessment. Results are displayed with high resolution in Google Earth for major coastal cities of interest. We will demonstrate these new capabilities and we illustrate the consequences at the local and global scales. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Frontiers in Marine Seismology

Oral Session · Friday 22 April · 4:30 PM Pacific

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Andrew Gase, University of Texas at Austin (agase@utexas.edu); Joshua Russell, Brown University (joshua_russell@brown.edu); Jianhua Gong, Scripps Institution of Oceanography (j4gong@ucsd.edu); Hannah Mark, Woods Hole Oceanographic Institution (hmark@whoi.edu); Guilherme de Melo, San Diego State University, Scripps Institution of Oceanography (gsampaiodemelo@ucsd.edu); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

Anisotropic Tomography of the Eastern North American Margin: Mantle Structure and Flow Across the Continent-ocean Transition

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The structure of the mantle across the continent-ocean transition of rifted margins has not been imaged in detail due to the sparsity of shoreline-crossing seismic datasets. The eastern North American margin (ENAM) Community Seismic Experiment provided a unique amphibious broadband ocean bottom seismometer (OBS) dataset. Shear wave splitting results along the margin, which measure seismic anisotropy and can reflect mantle flow, do not conform with plate motion or tectonic boundaries. To understand old rift-related and modern dynamical margin processes, we interrogated the structure and mantle flow across ENAM using joint isotropic/anisotropic shear-wave tomography. We utilized shear-wave splitting and travel times from both on and offshore stations. The velocity model shows a transition from ~1.5% fast, ~200 km thick continental keel to low velocity (compared to a regional average) and thinned lithosphere seaward. Short wavelength velocity anomalies can be explained by edge-driven convection and similar processes. These anomalies include the Central Appalachian Anomaly in Virginia, which is up to 5% slow. Velocity at 70 km depth is up to 2% slow offshore, with a 1.5% slow feature delineating the continent-ocean transition. The offshore velocity decrease may suggest an abruptly thinned lithosphere. We also imaged layered anisotropy throughout the region. Anisotropy is generally fast parallel to the margin (>1%) within the asthenosphere, suggesting margin parallel asthenospheric flow. The lower oceanic lithosphere preserves paleo-spreading-parallel anisotropy. The continental lithosphere has complex anisotropy with wavelengths <100 km, reflecting several Wilson cycles. These results demonstrate the complex and active nature of a rifted margin which is traditionally considered tectonically inactive.

Microplate Evolution in the Queen Charlotte Triple Junction and Explorer Region: New Insights from Microseismicity

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The Queen Charlotte triple junction / Explorer microplate region offshore British Columbia, Canada, is marked by poorly understood and rapidly evolving microplate tectonics. Although the region hosts abundant seismicity, it has received relatively scant attention in recent years due to its remote, offshore location. We use the Regressive ESTimator (REST) algorithm to generate a new catalog of automatically detected earthquakes, which, when merged with the existing Geological Survey of Canada catalog, yields the most extensive seismicity dataset offshore British Columbia to date. We apply double-difference relocation to these events and perform stress inversions using moment tensors for subregions within the study area. Our results reveal new insights into microplate deformation processes. The Revere-Dellwood-Queen Charlotte Fault system is posited to have evolved as a NW-migrating, transtensional stepover between Haida Gwaii and the Explorer ridge, under regional compression. Transtension has now ceased at the Winona basin where slip is partitioned between strike-slip along the Revere Dellwood Fault and compression along the paleo-Queen Charlotte Fault. Seismicity within the Explorer microplate is dominated by prominent, northeast-trending lineations that emanate from the Sovanco Fracture Zone and parallel the Nootka Fault Zone. Alignment of these features with spreading structures that bound the microplate suggests that its breakup is controlled primarily by a strength fabric inherited at spreading ridges. Stress inversions are dominated by near-vertical intermediate compressive stress reflecting the dominance of strike-slip faulting. Stress varies systematically between transpression to the north along southern Haida Gwaii and seafloor spreading to the south along the Juan de Fuca ridge.

Rapid Formation of Pack Ice in Shallow Coastal Waters, as Observed by Seafloor Distributed Acoustic Sensing

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Seismic instruments such as broadband seismometers and distributed acoustic sensors (DAS) have a demonstrated, but not fully tapped, potential for wide-scale and continuous *in situ* monitoring of a variety of near-surface environmental and anthropogenic processes. The continued development and adoption of the field of environmental seismology may contribute to geophysical monitoring efforts by opportunistically bridging spatial and temporal gaps in more specialized instrumentation networks. DAS, in particular, is attractive for development as a multi-geophysical observatory due to the prevalence of existing dark fiber infrastructure in regions with environmental, cultural or strategic significance. We present results from a seafloor deployment of DAS to the Beaufort Sea, Alaska, from November 2021. During the deployment we observed the transition of ambient noise characteristics from an "open water" state to an "ice-bound" state. A sea ice formation front was plainly visible on the DAS record and was observed to propagate 20 km seaward over a period of 8 hours. Satellite-based instrumentation were unable to record this event due to persistent cloud cover, low light conditions and orbital frequency. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

OBS Noise Reduction Using Harmonic-percussive Separation Algorithms

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The Investigation of the global Earth' structure benefits from the analysis of ocean bottom seismometer (OBS) data that allow an improved seismic illumination of dark spots of crustal and mantel structures in the oceanic regions of the Earth. However, recordings from the ocean bottom are often highly contaminated by noise and their noise level is much higher compared to land stations data especially on the horizontal components. Considering the high energy of OBS noises, the analysis of OBS signals like teleseismic earthquakes are complicated. Different approaches for noise removal of OBS recordings were suggested. Although being capable of removing noise from vertical component OBS recordings, most attempts on improving the signal to noise ratio on horizontal component data has been unsuccessful so far.

Inspired by the harmonic-percussive separation (HPS) algorithms used in Zali et al., (2021), we developed an OBS noise reduction method also applicable to horizontal component recordings. In our study, OBS noise with narrowband horizontal structures in the short time Fourier transform (STFT) spectrogram corresponds to unwanted harmonic components. Earthquake signals with transient-like characteristics and vertical exhibition in the STFT spectrogram are identified as percussive components and are considered as the signal of interest. Using modified HPS algorithms we isolate the horizontal structure from the vertical structure in the STFT spectrogram corresponding to harmonic and percussive components, respectively. We are able to separate OBS noise from the signal of earthquakes on both vertical and horizontal component recordings that leads to significant noise reduction of OBS records and increase the earthquake signal to noise ratio without distortion of the broadband earthquake waveforms. The applicability of the method is checked using real and synthetic data.

Novel Autonomous and Cabled OBS Solutions for Offshore Seismic Research

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Seismologists have historically focused more on terrestrial seismic research, due to the logistical and financial challenges presented by offshore research. Guralp has devloped technology which allows the seismology community to more easily monitor offshore seismicity, improving offshore seismic data resolution. This is due to systems such as the Aquarius autonomous ocean bottom seismometer (OBS) and world-leading engineering advancements in Science Monitoring and Reliable Telecommunications (SMART) cables.

Aquarius can be deployed autonomously on the sea floor for up to 18 months. The sensor works at any angle without using a gimbal system and can wirelessly transmit SOH and seismic data to the surface via an integrated acoustic modem. These features allow researchers to monitor and transmit data without offshore cabling, thereby reducing the logistical challenge associated with offshore OBS whilst maintaining some degree of real-time data transmission. Optional surface communications can be permanent (buoy-mounted), semi-permanent (wave-glider) or on demand (ship-of-opportunity or dedicated voyage).

Cabled solutions are also important, as they give users access to high-resolution data in real-time via a data cable linked to an onshore data centre. As an example, Guralp's Orcus cabled OBS provides these features as a complete underwater seismic station with observatory grade seismometer and strong-motion accelerometer in a single package.

SMART cables show great potential for increasing the number of cabled ocean observatory deployments in the future. Combining several applications into a single system, including seismic monitoring and telecommunications, large scale monitoring networks can be created cost effectively by combining efforts from several industries. As a practical example, Guralp is developing a demonstration SMART Cable system to monitor volcanic and seismic activity offshore in the Ionian Sea in collaboration with Instituto Nazionale Di Geofisica e Vulcanologia (INGV). This will be the first practical demonstration of this technology and there are plans for additional projects in the future.

SMART Repeaters: Sensor-enabled Submarine Fiber Optic Repeaters for Multi-scale and Multi-use Monitoring and Observing

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Innovative deep ocean monitoring technologies are crucial to catalyzing fundamental improvements in mitigating natural disasters, reducing human vulnerabilities and understanding environmental threats. An attractive but untapped resource is the global submarine fiber optic cable network, which carries over 95% of international internet traffic. Key components of undersea fiber optic cable systems are repeaters, which are placed every 60-100 km along the cable to provide optical signal amplification. Integrating environmental sensors, including seismic, pressure and temperature sensors, would enable real-time data collection for environmental and infrastructure threat reduction, natural disaster mitigation and cable system monitoring.

A unique technology that will revolutionize the utility of these cables is the SMART (Sensor Monitoring And Reliable Telecommunications) cable concept. Although the concept has been evaluated for over 10 years by an international suite of agencies and institutions, developing a SMART repeater requires substantial investment in research and development to validate a technology that could transform an industry. To date, no commercial manufacturer has allocated the resources to produce a prototype SMART repeater. To bridge this gap, we have obtained support by the National Science Foundation's Small Business Innovation Research (SBIR) program to develop a benchtop prototype SMART repeater.

Best-in-class SMART repeater sensors include a 3-axis accelerometer, absolute pressure gauge, and temperature sensor. Included with the sensors are data acquisition circuits with suitable dynamic range and precision, integration around a common communications module, an interface suitable for fiber optic cable spans up to 120 km in length, the software and firmware necessary to support the data path from the sensors to data storage servers, and precision timing for both time-stamps and frequency reference. The SMART repeater sensor system design is modular, thereby containing branch points for different sensors, as well as incorporation in different repeater housings or as standalone units.

Frontiers in Marine Seismology

Poster Session · Friday 22 April · Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Andrew Gase, University of Texas at Austin (agase@utexas.edu); Joshua Russell, Brown University (joshua_russell@brown.edu); Jianhua Gong, Scripps Institution of Oceanography (j4gong@ucsd.edu); Hannah Mark, Woods Hole Oceanographic Institution (hmark@whoi.edu); Guilherme de Melo, San Diego State University, Scripps Institution of Oceanography (gsampaiodemelo@ucsd.edu); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

An Improved Earthquake Catalog from the Alaska Amphibious Community Seismic Experiment (AACSE)

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The Alaska subduction zone produces a chain of volcanoes and abundant earthquakes, including the 1964 Mw 9.2 earthquake, the largest in the US. Great lateral variations exist along the strike of the Alaska subduction zone. Understanding the causes of these variations can help us better estimate and mitigate future earthquake hazards in the Alaska subduction zone. For this purpose, the Alaska Amphibious Community Seismic Experiment (AACSE), which included 75 broadband ocean bottom seismometers (OBSs) and 30 broadband onshore seismometers, was carried out from 2018 to 2019. Following the experiment, the Alaska Earthquake Center (AEC) processed the OBS dataset to detect earthquakes. We found, however, that a substantial number of events are missing in the AEC catalog, partly because the data quality of the OBSs varies greatly and thus requires varied treatment for individual stations based on signal-to-noise ratios. In this study, we improve the earthquake catalog by using a variable short-term-average/long-term-average (STA/LTA) detection threshold in a self-iteration process, which uses the initial locations of the earthquake and a lowered threshold STA/LTA detector to fetch as many phase arrivals as possible. Our improved earthquake catalog has one to two folds' increase of the total event number. The new events are found in not only the seismically active regions, but also the places where few events were observed in the AEC catalog.

Augmenting the Global Earthquake Database With OBS Phases for Key Events

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Significant heterogeneity in global seismic source locations, combined with a traditionally landbased sensor distribution, has resulted in highly non-uniform ray sampling of the Earth, leading to major gaps in global wave propagation information. This dearth manifests itself in poor constraint and resolution on global propagation models and reduced confidence in location for many earthquakes, particularly those occurring in coastal or oceanic areas. The steady increase in ocean bottom seismic deployments offers an opportunity to reduce this deficit by capitalizing on arrivals recorded in the many novel sensor locations that have been occupied by sensors for varied experiment durations. In general, due to the acknowledged high background noise levels in many seafloor settings, only phase arrivals from the largest earthquakes can be reliably identified, although the configuration of many such deployments as arrays allows for methods such as beamforming to improve the signal-to-noise ratio. We report on progress towards populating the Los Alamos National Laboratory's earthquake database with arrivals from a variety of OBS data sets, targeting first the best quality signals from earthquakes in key locations that can help to constrain our global propagation models.

Body Wave Imaging Beneath Oceans, Glaciers and Sediments Using Tuned Dereverberation Filters

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The surface of our planet is covered, in large portions, by oceans, glaciers and soft sediments. In these conditions, the teleseismic body wavefield is often severely contaminated by reverberations—especially trapped shear converted waves—hampering successful application of high-resolution imaging techniques for detecting sharp discontinuities within and across the lithosphere. While much effort has been dedicated, using standard spectral techniques, to describing and designing filters to correct for the effect of reverberations, much still needs to be done to adapt them to settings where seismic arrays are deployed above subsurface structure that is highly complicated. In this study, we adapt a technique widely used in speech enhancement to address this challenging problem of reverberation elimination. We demonstrate, using synthetic and real data experiments, that our new approach of automatically tuning the dereverberation filters using seismic data alone, can eliminate the signature of reverberations, even in settings not previously explored. We expect that our approach will enable the use of the scattered body wavefield for high-resolution imaging.

Characterizing the Acoustic Structure of the Southeastern Caribbean Sea Using Multichannel Seismic Reflection Data

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Multichannel seismic reflection profiles acquired in the southeast Caribbean along the northern margin of the South American continent offshore Venezuela reveal seismic reflectivity within the water column to depths of 1000 m. The data were acquired perpendicular to the westward flowing water current that dominates this region, and to the Caribbean Low Level Jet (CLLJ) winds that drive the troposphere-sea surface interaction, and are ideally positioned to capture the presence and extent of the vertical mixing between wind-driven, shallow circulation, and the deeper, thermohaline water masses, as well as their modulation by the coastal and Leeward Antilles bathymetric morphology across which the whole southeast Caribbean ocean current is flowing. The multichannel seismic reflection data interpreted in conjunction with expendable bathythermograph (XBT) and conductivity-temperature-depth (CTD) measurements indicate that seismic reflectors correspond with variations in temperature and salinity seen in the shallow surface (> 200 m) and in the thermocline (200 m – 1000 m). Below the thermocline, reflectivity fades quickly and disappears altogether. Within the thermocline, a region of low reflectivity is also observed, spanning ~25 km in width and extending for ~100 km across the profiles analyzed. Seismic data overlain by HYbrid Ocean Coordinate Model (HYCOM) water velocity profiles show that this semi-transparent region correlates to an abrupt decrease in water velocity. We propose that the reduction of reflectivity may be caused by lack or reduction of mixing in this region caused by the interaction of the westward flowing current with the bathymetric high of the Margarita Island ~100 km windward to the east. Changes in depth of the base of the reflectivity also correlate with seafloor highs and slopes, indicating control of bathymetry on the structure of ocean internal waves.

Fault Architecture of the Westmost Gofar Transform Fault, East Pacific Rise

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Oceanic transform faults (OTFs) are apparently simple tectonic plate boundaries. However, their structures are surprisingly complex as manifested through various seismic and aseismic slip modes. Here we use ocean-bottom-seismometer data collected during a 2008 marine experiment to study the westmost Gofar transform fault. The dataset records the end and early stages of a M6 earthquake seismic cycle and offers a unique opportunity to investigate the fault architecture, seismicity evolution and their inter-relations in regulating earthquake rupture processes. We identify multiple segments along the Gofar fault that have distinct seismic behaviors. In addition to previously identified locked and barrier zones, we find the segment connecting to the East Pacific Rise is characterized by quasi-periodic swam activities. Particularly, this segment hosted a 2-week long swam in December 2008 showing a clear eastward migration and breaking a newly identified shallow fault patch. In between this swarm segment and the 2008 M6 mainshock zone, seismicity is influenced by both the mainshock and the December swarm. Previous studies show that the barrier zone east of the mainshock zone hosted abundant foreshocks preceding the M6 event and halted its active seismicity afterwards. Our new analyses show that the barrier zone has two layers of earthquakes that responded to the M6 earthquake differently. Our results suggest highly heterogenous fault architectures along strike, and fault patches interact and trigger each other over a broad temporal scale. It is unclear how such heterogenous structures were developed at this geologically simple region, but we speculate that the fault architecture variations result from complex fault geometry, fluid-rock interactions and transient tectonic events. Our findings generally agree with the multimode-slip-partitioning mechanisms of OTFs, but also deviate from the synoptic view, highlighting complex internal fault structures at multiple scales.

Insights into Bend-faulting and Mantle Hydration at the Marianas Trench from Seismic Anisotropy

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Oceanic lithosphere approaching deep ocean trenches tends to form bend faults, which promote water circulation and the formation of hydrous minerals in the crust and mantle of the incoming plate. As the plate subducts, these minerals can dehydrate into the mantle wedge, generating the melts that feed arc volcanoes, or subduct fully into the deeper mantle. Balancing the global water budget requires an estimate of the amount of water recycled to the mantle by subduction, but current estimates for water fluxes at subduction zones span several orders of magnitude, mainly because of large uncertainties in the amount of water carried in the lithospheric mantle of the incoming plate.

We use active source seismic refraction data collected on the incoming plate at the Marianas trench to measure azimuthal seismic anisotropy in the uppermost mantle and assess the degree of faulting and associated serpentinization of the uppermost mantle based on spatial variations in the observed anisotropy. We find that the fast direction of anisotropy varies with distance from the trench, rotating from APM-parallel at the eastern side of the study area to approximately fault-parallel near the trench. This suggests that a coherent set of bend-faults is beginning to form at least 200 km out from the trench, although the extrinsic anisotropy signal from the faults does not substantially overprint the signal from preexisting mineral fabrics until the plate is ~100 km from the trench. The average (isotropic) mantle velocity decreases slightly as the plate nears the trench, consistent with the formation of serpentine minerals. The 4θ-periodic component of anisotropy is strongest immediately beneath the Moho and decreases in strength over the ~7 km below the Moho sampled by our data. Preliminary interpretation suggests that the observed spatial variations in anisotropy can be explained by serpentinization localized along pervasive, trench-parallel faults or joints.

Investigating the Mantle Transition Zone Below the Central Pacific With Ps Receiver Functions From the NoMelt Experiment

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The structure and nature of the 410 and 660 km velocity discontinuities bounding the mantle transition zone (MTZ) reveal critical information regarding the behavior of mantle flow. Their nominal depths and velocity jumps provide a proxy for the thermal and compositional state of the mantle as these discontinuities result from mineral phase transitions. We examine the utility of broadband waveform data collected on 16 high quality NoMelt OBS stations from 12/2011 to 01/2013 to compute Ps receiver functions to image the 410 and 660 km discontinuity depths and associated velocity gradients throughout the MTZ. The NoMelt experiment is located southeast of Hawaii, spanning a 600x400 km region of mature (~70 Ma) oceanic lithosphere. Our preliminary culling of the NoMelt dataset using these criteria: Mw > 6.2, event depth <50 km and epicentral distance 30-90 degrees yields ~1000 piercing points at both discontinuity depths in a pattern with significant overlap to allow for stacking. The OBS waveform data require more careful processing than typical land station recordings due to contaminations from instrument tilt and compliance noise, which can be minimized on the vertical component using data on the horizontal and pressure channels. Previous studies using the NoMelt data indicate that secondary microseism and/or tilt noise on the horizontal components appears to peak between 2-5 seconds period and that our best window of observation may be closer to 10 - 30 seconds period. We plan to use the traditional method of deconvolving the vertical from radial component then migrate the receiver functions to depth using the CCP technique. Mineral physics modeling of the discontinuity depths and velocity jumps will be done by exploring the relationship between velocity, temperature and composition (basalt fraction) using the Perple_X thermodynamic code and the elastic parameter database of Stixrude and Lithgow-Bertelloni to characterize this region of ambient mantle.

Long-term Earthquake Catalog for the Endeavour Segment of the Juan De Fuca Ridge Highlights the Influence of Propagating Rifts on Hydrothermal Venting

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The Endeavour Segment of the Juan de Fuca ridge is well known for its five vigorous and chemically distinct hydrothermal vent fields, all uniformly spaced along the axis of the center of the segment. Geological evidence suggests that unlike those at other intermediate- and fast-spreading ridges, the Endeavour hydrothermal vent fields have persisted for centuries without extrusive volcanic disturbance, despite the inflated nature of the central portion of the segment and the presence of a robust mid-crustal axial magma chamber (AMC). Unravelling the relative roles of magmatism and tectonism in supporting hydrothermal venting requires long term seismic observations. We achieve this by combining new observations from the Ocean Networks Canada cabled observatory, whose multi-station seismic network came online at the Endeavour in 2016, with past autonomous ocean bottom seismic monitoring experiments in 1995 and 2003-2006, producing a unique catalog of seismicity that spans two decades.

Off-axis seismicity patterns suggest that the rapidly advancing propagating rifts associated with the overlapping spreading centers at both ends of the Endeavour segment now extend to within a few kilometers of the segment center. The most vigorous vent fields are aligned with the inferred locations of the rift tips. On-axis, the catalog reveals that mid-crustal seismicity associated with magma chamber inflation is temporally variable, whereas very shallow seismicity, which we infer is linked to the propagating rifts, is persistent throughout the catalog. We propose that deformation associated with the propagating rifts provides the time-independent fracturing needed to support the longevity of the vent fields and pin their location in place. We further speculate that increased permeability above the AMC, driven by the rift tip tectonics, allows increased volatile degassing that leads to the observed paucity of extrusive volcanism during dike emplacements.

Looking for Love Across the Hawaiian Swell

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Love waves—transversely polarized surface waves—are useful for estimating radial anisotropy and can provide valuable constraints which can help discriminate between causative models explaining underplating beneath the Hawaiian swell. However, it is challenging to extract the Love wave signal from ambient noise recordings on submarine seismograms. This may primarily be due to the signal distortion on horizontal seismograms caused by tilt noise. In this study, we use the amphibious seismic network (submarine and land-based) across the Hawaiian swell to investigate techniques for improving the detection of short-period love waves. First, we conduct various experiments to test the hypothesis that Love wave signal distortion is due to interference from tilt noise. We then explore how this noise source varies temporally and spatially, and see if normalizing for its effects improves Love detection. Finally, we investigate other methods like wavefield decomposition and high-resolution multispectral analysis, which may improve detection in the presence of tilt-noise or other sources of signal distortion.

Next-generation Broadband Seafloor Instruments To Support New Discovery

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The densification of offshore observatories is the next important challenge for scientists as described in “A Vision for NSF Earth Sciences 2020-2030: Earth in Time” (National Academies of Sciences, Engineering and Medicine, 2020).

Nanometrics is combining our latest land based technology with our proven OBS technologies to enable the next steps in offshore observation. Specifically, we are building both 360 second and 120 second corner observatory class seismometers with the same performance specifications as land based instruments, but in a form factor allowing deployments to 6000m. These seismometers come in a form factor unique to the OBS community allowing exceptional advances in SWaP (size, weight, and power), critical to reducing the expensive logistics of OBS work, and are suitable for autonomous and cabled stations. Power usage and volume are reduced 60-70% versus previous generation options.

These new instruments expand our range of products enabling new ocean bottom science, reducing integration risk and time to deploy, while improving outcome certainty.

Upper-mantle Shear Attenuation and Velocity From Ocean-bottom Observations in the Pacific

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Shear attenuation (Q^{-1}_{μ}) and velocity (V_S) are key parameters for understanding the structure and evolution of the oceanic lithosphere-asthenosphere system and grain-scale deformation processes. Recent proliferation of dense ocean-bottom seismometer (OBS) arrays in the Pacific provides an opportunity to measure both Q^{-1}_{μ} and V_S at high resolution at a range of seafloor ages, illuminating the age-dependence of anelasticity and corresponding temperature and melt variations in the upper mantle. Yet, measuring Rayleigh-wave attenuation (Q^{-1}) in the oceans remains a challenge due to complicating factors that impact wave amplitudes such as OBS tilt and compliance noise, focusing/defocusing effects and overtone interference.

We adapt a wave-front tracking approach to measure Rayleigh-wave Q^{-1} and phase velocity (20–150 s) at five OBS arrays in the Pacific ranging in age from

3–125 Ma. Our method utilizes a cross-correlation based approach to make differential phase and amplitude measurements on tilt/compliance-corrected seismograms. The Laplacian fields of phase and amplitude are used to account for the effects of wavefield focusing/defocusing and finite-frequencies, respectively, but are difficult to estimate in the presence of noise. We directly invert differential measurements for maps of phase and amplitude gradient, which allows for explicit control on Laplacian smoothness. Synthetic tests demonstrate that this approach robustly estimates the Laplacian fields, accurately recovering intrinsic Q^{-1}. We invert average Q^{-1} and phase velocity measurements for depth dependent Q^{-1}_{μ} and V_S to 300 km depth at each of the five locations in the Pacific. Temperature and melt fraction are quantified in the low-velocity zone (LVZ) by jointly interpreting Q^{-1}_{μ} and V_S within a Bayesian framework. The classic half-space cooling model is unable to explain our observations. At the youngest ages (<10 Ma), 2–5% partial melt is required within the LVZ, while at the oldest ages (>70 Ma), temperature estimates are up to 400°C hotter than the half-space cooling geotherm and are better explained by a plate cooling model.

Using Machine Learning to Improve Earthquake Catalogs for Amphibious Seismic Networks: Application of EarthquakeTransformer to the Alaska Amphibious Community Seismic Experiment

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We use the machine-learning (ML) earthquake detection and picking algorithm EarthquakeTransformer (EQT) to expand the existing catalog of earthquakes recorded during the Alaska Amphibious Community Seismic Experiment (AACSE) in 2018-19. AACSE included 30 onshore and 75 ocean-bottom seismometers (OBS) deployed along the Alaska-Aleutian Trench from Kodiak Island to the Shumagin Islands. Knowledge of offshore seismicity is key to understand subduction zone seismic hazard generally, and ML methods may be able to detect orders of magnitude more small earthquakes using offshore seismic data. Yet, many ML methods are developed, trained and tested with only onshore seismic data. EQT, for example, is trained on 1 million earthquake and 300 thousand noise waveforms, all recorded on land.

First, we test EQT against the existing AACSE earthquake catalog generated by the Alaska Earthquake Center. We apply the default EQT model to pick P and S waves in the AACSE seismic dataset, first applying a band-pass filter of 1-50Hz (land) or 5-20Hz (OBS). EQT finds 58% of P and 61% of S arrivals within 300 km epicentral distance, the max epicentral distance in the EQT training data. This relatively poor performance compared EQT's test dataset (99% of P and 96% of S) suggests re-training with amphibious data may be necessary. Despite shortfalls, we are able to use EQT plus a grid association method to detect more small earthquakes in AACSE. In the region west of Kodiak Island, we find roughly 40% more events. Previously-observed along-strike variation in seismicity rate persists: in both the thrust zone and outer rise, the Semidi segment has relatively few earthquakes while the Shumagin segment has many. Quantifying spatial and temporal patterns of microseismicity in the region prior to the July 2020 M7.8 Simeonof and July 2021 M8.2 Chignik earthquakes may provide new insight into stress or rheological conditions in the thrust zone that prepare the plate interface for large-scale ruptures.

Waveform Modeling of Seismo-acoustic Records From MERMAID Instruments in the Pacific

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A fleet of passively drifting profiling floats equipped with hydrophones, named MERMAID (Mobile Earthquake Recording in Marine Areas by Independent Divers), monitors worldwide seismic activity from inside the oceans. The instruments are programmed to detect acoustic pressure conversions from local, regional and teleseismic earthquakes from within the water column–usually around 1500 m depth–over repeated dive cycles. Reporting short seismograms autonomously in near-real time, the instruments are not usually recovered, but they allow for requests from a one-year buffer. About fifty instruments deployed in French Polynesia in 2018 and 2019 remain actively drift in the South Pacific. Together they have yielded an unprecedented data set of sound recorded at depth in the frequency range of 0.1–20 Hz. We present highlights from our earthquake catalog and discuss the changing character and cause of the background noise. We use the instrumental response function to convert the raw hydrophone records to time series of acoustic pressure. We focus on modeling in detail the shape of earthquake-generated waveforms within the short time window surrounding the first arrival. Understanding and correcting for the effects of the oceanic layer on seismo-acoustic waveforms will ensure that MERMAIDs pressure records can be used for tomographic imaging of Earth's interior. We use SPECFEM-2D, a high-resolution spectral-element method for modeling seismic-acoustic wave propagation to determine the transfer function between the displacement field at the seafloor and the hydroacoustic signals recorded by MERMAID within the water column. Parameterizing teleseismic arrivals as slanted-planar or nearly spherical wavefronts allows us to consider the influence of the oceanic wavespeed profile, ocean-bottom topography and the crustal elastic structure in the neighborhood of the seismo-acoustic conversion point. This research informs our use of global wave propagation codes AxiSEM and InstaSeis, to generate synthetic seismo-acoustic waveform for global earthquakes, which we compare to our observations in preparation for waveform tomography.

Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage

Oral Session · Wednesday 20 April · 4:30 PM Pacific

Conveners: D. Parker Sprinkle, University of Washington (dpsprink@uw.edu); Hunter A. Knox, Pacific Northwest National Lab (hunter.knox@pnnl.gov)

Multiplet Analysis for Identification of Fractures in Areas of Fluid Migration: A Comparative Study of Seismicity Clusters From the Geysers Geothermal Field, California and Song Tranh 2 Water Reservoir, Vietnam

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Groups of seismic events with very similar waveforms, i.e. multiplets, have been successfully used for identification of subsurface fractures in areas of underground fluid injection or beneath active volcanoes. Another type of geological setting potentially influenced by fluid migration is an area of artificial water reservoir, e.g. accompanying a hydropower plant. In such settings triggered seismic events occur due to reservoir loading and underground fluid penetration resulting in pore pressure increase. In this study we compare the utility of multiplet analysis for imaging fracture network and geological structures at two different sites: vicinity of Prati-9 and Prati-29 injection wells at The Geysers geothermal field (California, USA) and Song Tranh 2 water reservoir (Vietnam). At both sites we identify groups of 'multiple seismic events' (ME) with cross-correlation of seismograms ≥ 0.8 and perform the double-difference relocation. With this method, in both cases we manage to delineate underground structures hosting significant part of seismicity. Moreover, we perform temporal analysis of ME occurrence in relation to injection rate and water level. In case of The Geysers seismicity cluster, we identify a structure exhibiting an inverse relation of seismic activity to injection rate and significantly lower values of static stress drops in comparison with other seismic events. We interpret it as a fault experiencing permanent aseismic movement. In case of Song Tranh 2 reservoir, we manage to distinguish two separate geological structures activated with time delay of several months.

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Supervised and Unsupervised Machine Learning Applications for Induced Seismic Data Analysis at Illinois Basin Decatur Project Site

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Quantifying in-situ subsurface conditions and understanding of slip mechanisms along the faults are critical to reducing risks of induced seismicity and improving subsurface energy activities. In this work, we present a novel integration of both supervised and unsupervised machine learning methods to process and characterize microseismic data obtained at the Illinois Basin - Decatur Project (IBDP) site where a CO_2 injection process lasted three years (2011-2014) as a field demonstration project. For detection and phase picking of microseismic (MS) data, a set of preprocessing and data augmentation techniques were used to feed waveform time-frequency information to a convolutional neural network (CNN) to accurately detect true events and estimate p and s wave arrivals (>98% accuracy with testing data). After training CNN-based detection model with data from MS cluster #2 at the IBDP, the CNN model was retrained with another cluster #4 to evaluate transfer learning approach. In addition, the original PhaseNet model that was developed based on conventional seismic data was retrained to MS events to accurately obtain p and s arrival times. In both cases we achieved higher true event detection rate compared to the original catalog (manual picks). We discuss the advantages of each method in terms of their ability to detect and/or phase pick. Second, an unsupervised machine learning using the Nonnegative Matrix Factorization and the Hidden Markov Model was used to construct a time dependent probabilistic architecture. The resulting spatio-temporal patterns are taken as fingerprints of spatio-temporal waveform characteristics related to changes in pore pressure and stress caused by CO_2 injection. This study will improve characterizing seismic waveforms by machine learning approaches and the detection of low-magnitude seismic events leading to the discovery of hidden fault/fracture systems. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Coupling Induced Seismicity to Permeability Using Spatial Correlation Analysis of EGS Data

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Direct association of microseismicity with crustal fluid flow properties has long been assumed, but for a variety of reasons it has been difficult to define a close spatial association using subsurface measurements. We show here that rock-fluid-seismicity interaction are the result of a critically stressed brittle crust exhibiting power-law scaling distributions of rock porosity and permeability. We demonstrate these results using deep borehole seismic observations of microearthquakes induced during an Engineered Geothermal System project in Finland. In quantitative terms, the microearthquake clustering found in the Finnish data fit a two-point spatial correlation function of the form $\Gamma meq(r) \sim 1/r^{1/2}$.

This type of rock-seismicity interaction arises from two empirical porosity and permeability relations which are widely observed in brittle rock: (i) a power-law spectral scaling of crustal porosity/permeability spatial fluctuations seen in well-logs: $\varphi(:)$, $S[\varphi(k)] \sim 1/k$, k = spatial frequency 1/km < k < 1/m; (ii) well-core permeability distributions given by $\kappa \sim \exp(\alpha\varphi)$ where the parameter α has values so that $\alpha\varphi$ is bounded between 3 and 5 for mean formation porosity range between $0.003 < \varphi < 0.3$ as seen, for example, in basement crystalline and clastic sedimentary rock. The correlation function $\Gamma meq(r) \sim 1/r^{1/2}$ for induced seismicity is predicted by applying the Wiener-Khinchin theorem to relation (i): $S[\varphi(k)] \sim 1/k \sim \int \exp(ikr)\Gamma(r)dr$. This expression directly relates the porosity and permeability power-law scaling seen in well logs and cores to the correlation function seen in the induced-microearthquake data. This spatial association of fluid flow pathways with low-level energy seismic release has also been observed in shale formations undergoing frack-stimulation. These data indicate that the observations and quantitative results presented here complete the linkage sought at in the beginning of our abstract.

It's in the Eye of the Beholder: Previously Discarded Seismic Noise May Tell Us Just as Much About Anthropogenic Fluid Injection as Detected Earthquakes

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For a long time, detected events were thought of as the only useful information that could be gleaned from continuous seismic recordings. However, in recent years it has been shown that the "noise" that was often discarded and filtered out can actually be used to determine temporal and spatial variations in seismic wave properties, related to changes in the local stress field. In a volcanic or reservoir environment, such changes may relate to the presence (or absence) of fluid or changes in fault/fracture characteristics. Here, we investigate temporal and spatial velocity variations using ambient seismic noise in an area dominated by hydraulic fracturing and waste-water disposal in NE British Columbia between January 2020 and January 2022. In addition to determining long-term changes in the ambient seismic noise over the 2 year period, we also investigate whether spatial differences in noise variations can be related to known operations, and/or to a number of local felt seismic events ($M_L > 3$) that have occurred in the area. Analysis of ambient seismic noise in this area of British Columbia has the potential to determine local changes in pore fluid pressures, as well as the evolution of fracture networks, which may be useful for mitigation strategies for induced seismicity.

Activation of Optimally and Unfavorably Oriented Faults Within the Oklahoma LASSO Nodal Array

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The LArge-*n* Seismic Survey in Oklahoma (LASSO) dense nodal array with >1800 sensors captured multiple small (<1 km in length) seismogenic faults within its bounds. Using machine-learning based event detection methods (EQTransformer, Mousavi et al., 2020), we expanded the LASSO catalog by a factor of two to a total of roughly 2000 earthquakes located within the array. Using this extended catalog and FaultID (Skoumal et al., 2019) we algorithmically identify 38 separate seismogenic fault planes within the array's footprint, a region covering 25 by 32 km. The focal mechanism catalog within the array is increased from 23 to 1306 events using machine learning methods and the model of Ross et al., 2018 to identify and characterize waveform first motions. The high-quality focal mechanisms within this catalog were then used to estimate the local principal compressive stress direction within the array's bounds. The identified faults' orientations are then compared to the inverted stress field to determine if the faults are optimally oriented. Optimally oriented faults require small stress changes to trigger failure, while unfavorably oriented faults require larger stress changes, assuming the same amount of accumulated stress on each fault. For induced earthquake sequences, the source of this stress change could be static stress changes from earthquake interactions and/or dynamic pore pressure changes. Within the context of the identified fault structures and their orientation to the local stress field, the spatiotemporal characteristics of each seismogenic fault's behavior are used to understand if pore pressure or earthquake interactions played the dominant role in each sequence's evolution.

Imaging, Monitoring and Induced Seismicity: Applications to Energy and Storage

Poster Session · Wednesday 20 April · Conveners: D. Parker Sprinkle, University of Washington (dpsprink@uw.edu); Hunter A. Knox, Pacific Northwest National Lab (hunter.knox@pnnl.gov)

A Strategy for Choosing Red-light Thresholds to Manage Hydraulic Fracturing Induced Seismicity in North America

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Induced earthquakes caused by hydraulic fracturing (HF) are a growing concern, with risks that are often managed by traffic light protocols (TLPs). Here, we apply a risk-informed strategy for choosing TLP red-light thresholds. We utilize a combination of probabilistic maximum magnitudes, formation depth, site amplification, ground motion relationships, felt/damaging shaking tolerances, and population information to simulate the spatial distribution of nuisance and damage impacts. We apply this approach to many of the prominent North American shale plays that have caused earthquakes: the Horn River Basin, the Duvernay Formation, the Montney Formation, the Utica Shale, the Marcellus Shale, the SCOOP & STACK play in Oklahoma, the Eagle Ford Formation, and the Delaware Basin. We find that induced earthquake impacts are spatially heterogeneous, depending most strongly on population density. These spatial heterogeneities vary on different length scales, depend-

ing on if they are related to nuisance (longer range, 100s kms) or damage (shorter range, 10s kms). Because of this variability, we suggest an approach that sets red-light magnitudes based on tolerances to nuisance and damage risks (varying between Mw 2.0-5.0). Comparison of the results between North American shale plays where TLPs have been enacted suggests that nuisance risks have been an influencing factor in determining red-light thresholds. Our method provides quantitative guidelines for traffic light protocols designed in a risk-informed manner that retains the implementational simplicity of magnitude-based thresholds. In addition, our results provide a benchmark for jurisdictional nuisance tolerances that future TLPs could be guided by.

Detecting Fluid Movement in Seismogenic Faults Using Earthquake Attributes in Oklahoma

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We present analysis of the earthquakes that occurred in Quinton, Oklahoma that exhibit varying dominant frequency content over the course of the sequence. The Quinton sequence is characterized by cycles of fluctuating seismic rates since 2019 of low to moderate-sized earthquakes. The seismic activity temporally coincides with both waste fluid disposal and hydraulic fracturing activity. The waste fluid disposal zone is within the Simpson group that is atop the Arbuckle group. We apply waveform modeling and broadband seismograms analysis to detect fluid movement on the seismogenic faults. We reconstruct frequency variation in the recorded seismograms' waveforms by finite-difference forward modeling waveform propagation in a 2D crustal model that fits the local stratigraphic layering. The numerical modeling analysis indicates earthquakes with a focal depth that are within more fluid-saturated formations are characterized by relatively low frequency content compared to those from less saturated formations. The results match the observed frequency attributes in the earthquake records. We further analyze the ratios of the high and low frequency energy in the earthquakes (i.e., frequency index) to characterize the temporal change in frequency content of the earthquakes. Preliminary analysis indicates the notable earthquake swarm within the sequence occurs in a period dominated by relatively low frequency index. We further forward model the swarm earthquakes to constrain the focal depths in order to determine the formations where they occur. We will present updated analysis that could highlight possible fluid propagation through the seismogenic faults.

Diverse Fault Architectures and Stress States Evolutions of Induced Earthquake Sequences Revealed by High-resolution Focal Mechanism Solutions

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The increasing seismicity and improved seismic observation network in recent years reveal diverse spatiotemporal evolutions of earthquake sequences in Oklahoma. The rich dataset offers an opportunity to better understand the roles of fault structure and stress states on sequence evolutions.

In this study, we select four well recorded sequences with two sequences having M≥5 earthquakes (Fairview, Cushing) and two sequences with maximum magnitude around M4 (Guthrie, Woodward). The two M5 sequences are dominated by aftershocks with weak spatial migration, while the two M4 sequences are typical long-duration swarms with clear diffusive migration.

Detailed analyses of fault structure and stress states show distinct characteristics for these sequences. The main fault structures in Cushing and Fairview are near-vertical strike-slip faults with dominantly strike-slip faults and around 80% of the small earthquakes are optimally oriented. In contrast, Guthrie and Woodward sequences show more complex fault structures with varying dipping angles along depth and a mix of strike-slip faulting and normal faulting. The percentage of optimally oriented events is 60% and 53% for Guthrie and Woodward, respectively. For Cushing and Fairview, the fault planes for the small earthquakes leading up the larger events are mostly optimally oriented, and the large events (M>4) activated some non-optimally oriented fault planes. For Guthrie and Woodward, the fault activation started along optimally oriented segments and poorly oriented segments are progressively activated with increased pore pressure. These detailed analyses demonstrate that fault architectures and heterogeneous stress states strongly influence the spatiotemporal evolutions of seismicity and largest possible event hosted.

Exploring the Role of Wastewater Disposal in Causing Recent Increases in Seismicity in Central and Northern Kansas

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Prior to 2013, Kansas seldom had more than one or two felt earthquakes in a given year. However, in 2014 the seismicity rate increased dramatically in Kansas to an average of 42 earthquakes per year with magnitudes greater than 3. Most of the seismicity (two-thirds) has been in the south-central part of Kansas, in particular Harper and Sumner counties, near the Oklahoma border which has been attributed to large-volume saltwater-injection wells from oil and gas production. Within the last 3 years there have been more magnitude 4 and greater earthquakes than seen in years prior with 9 events since 2019, including two with Mw > 4.5. Interestingly, 8 of those 9 magnitude 4+ events are north of the more active and well-known Harper and Sumner counties. A recent study by the Kansas Geological Survey on the seismicity in Hutchinson, Kansas, just north of the south-central region of seismicity, attributed seismicity in Hutchinson to both local and regional disposal wells. If high-rate disposal wells near the Oklahoma border nearly 90 km away can contribute to seismicity in Hutchinson, then what other regions in Kansas may be affected by high-rate disposal wells at a distance. We use earthquakes from the Kansas Geological Survey from 2000 to 2021 and well data from the Kansas Corporation Commission to investigate seismicity in north and central Kansas and whether or not they are related to oil and gas operations such as waste water disposal. In particular, we focus on examining swarms with increasing seismicity rates that have resulted in magnitude 4+ earthquakes.

Fault Activation by Induced Aseismic Slip: Scaling Behaviour and New Observations

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For natural faults systems, slow (aseismic) slip is increasingly recognized as a fundamental component of seismogenic processes. Although slow-slip events occur on timescales that are orders-of-magnitude longer in duration than normal earthquakes, they exhibit similar power-law scaling in terms of duration versus moment, including a change in scaling behaviour at the break between unbounded and bounded areal rupture growth. Aseismic slip is the expected behaviour for fault systems characterized by velocity-strengthening frictional rheology, including cases where faults contain certain clay minerals and organic carbon that commonly occur in unconventional petroleum systems. In the last few years, direct and indirect observations point to aseismic slip processes during hydraulic-fracturing operations. Documented cases include precursory aseismic slip accompanied by microseismicity prior to a MW 4.1 event, inferred progressive slow-slip fault activation with arrested rupture, and a MW 5.0 slow-slip event that produced casing deformation. Several of these cases use technology to complement traditional seismological observations, such as Distributed Acoustic Sensing (DAS) and satellite Interferometric Synthetic Aperture Radar (InSAR).

Improving the Catalog of Induced Seismicity in Southeastern New Mexico

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The New Mexico Tech Seismological Observatory (NMTSO) has been monitoring seismicity in southeastern New Mexico continuously since 1990. Beginning in 2018, the number of seismic events in this area has increased significantly, rising from fewer than 50 events larger than magnitude 1.8 detected per year prior to this time period to over 250 in 2020. The largest was a M4.0 event on July 19, 2021 near the border of Texas and Lea and Eddy counties in New Mexico. The rise in the number and size of earthquakes in southeastern New Mexico has prompted concern from regulatory agencies and the public. Due to the location of the earthquakes near the WIPP site, it will be essential to better characterize the seismicity to understand its ties to wastewater injection and fracking. Here we describe efforts being undertaken to improve the

earthquake catalog for this region. We have investigated the extensive data catalog of events using template matching to detect additional seismic event and performed earthquake relocation using a recently developed 3-D velocity model of the greater Permian Basin. Results show that seismicity was distributed in several spatially isolated clusters. Some of them are located around previously mapped fault traces, but some of the earthquake clusters exist in places with no previously mapped fault traces. but show apparent clustering patterns. These results will significantly improve our historic earthquake catalog and allow us to conduct further analyses to better understand the earthquake hazard in this region.

Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination

Oral Session · Wednesday 20 April · 4:30 PM Pacific

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Web Interfaces and Web Services for Open Coordinated Strong-motion Data Dissemination in Europe

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We present the strong-motion seismology services coordinated by the ORFEUS (Observatories and Research Facilities for European Seismology) community in the greater European region, namely the Engineering Strong-Motion (ESM) and the Rapid Raw Strong-Motion (RRSM) databases and associated web interfaces and web services (https://orfeus-eu.org/data/strong/). The RRSM is a fully automated downstream product of the European Integrated Data Archive (EIDA; https://orfeus-eu.org/data/eida/), tailored to rapid dissemination of earthquake shaking information, including on-scale broadband velocity data. The ESM delivers manually processed waveforms and reviewed earthquake information at a reasonable time delay and includes offline strong-motion data from other non-EIDA sources, such as the ITalian ACcelerometric Archive (ITACA). The ESM is the reference database–in terms of both recorded data and site metadata–for harmonized seismic hazard and risk studies in Europe (http://www.efehr.org). The RRSM and ESM are complementary services designed for a large range of stakeholders, including scientists, engineering practitioners and the educated general public. These systems are managed, maintained and reviewed by selected members of the seismological community in Europe, including strong-motion observatories and expert users. Global access and usage of the data is encouraged. Commercial usage of the data is facilitated by adopting open licensing schemes for both raw data and derived information. Appropriate acknowledgment of the data providers is strongly encouraged, based on full citations of the seismic networks including digital object identifiers.

Identifying Strong-motion Instrument Metadata Inconsistencies Before and After Earthquakes

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The US Geological Survey (USGS) National Strong Motion Project (NSMP) recently modernized its workflow to transition from manual to near real-time data processing and review, providing a notable increase in processed strong-motion data available to the community at the Center for Engineering Strong Motion Data (CESMD). Here we highlight the NSMP's recent development of metadata quality checks designed to highlight station metadata inconsistencies before the next significant earthquake. Pre-earthquake checks include flagging stations where the full scale of the sensor exceeds the paired datalogger and identifying cases where the total combined sensitivity of the datalogger and sensor do not match anticipated scale values provided by datacenter metadata sources. Post-earthquake checks include methods for flagging potentially anomalous peak ground acceleration values by sorting stations by distance from the epicenter and comparison to estimates from regional ground motion models. The goal of this effort is to move toward a more efficient, fully automated data processing system. These datasets are valuable resources for the earthquake engineering community for designing earthquake-resistant structures as well as for advancing our understanding of earthquake source, path and site effects.

Improving the Development Pipelines for USGS Earthquake Hazards Program Real-time and Scenario Products

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The real-time and scenario products of the U.S. Geological Survey (USGS) Earthquake Hazards Program, such as the ComCat catalog, Did You Feel It? (DYFI?), ShakeMap, ShakeCast and PAGER, are highly visible and used by a variety of stakeholders. We propose two significant enhancements to the development pipelines for the Earthquake Hazards Program real-time and scenario products that have far-reaching benefits. First, we propose incorporating processed and archived ground-motion records into the data streams for real-time products. This would increase reproducibility and transparency for ShakeMap and downstream products that serve critical functions in earthquake response and research. It would also provide comprehensive, open access databases of ground-motion intensity measures time histories that are fundamental tools in most engineering seismology studies. Second, we propose extending the pipeline for scenario products to fully complement the real-time pipeline. This would define a comprehensive set of standards for archiving scenarios, including 3D ground-motion simulations, and allow the suite of scenario products to be disseminated in the same way as real-time products. These enhancements would increase the value of important Earthquake Hazards Program products and transform the way USGS scientists and the engineering seismology community conduct ground-motion research.

Systematic Quality Control of National Strong Motion Project Structure Instrumentation Using Teleseismic Data

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Recordings of large earthquakes from structures (e.g., buildings, dams, bridges) are critical for understanding their performance during strong shaking. These data help with structural health assessments following potentially damaging events and can also inform the design of future earthquake-resistant structures. The U.S. Geological Survey (USGS) National Strong Motion Project (NSMP) currently operates ~190 structural arrays with over 3200 channels in the United States. Strong-motion records with acceleration, velocity and displacement files are processed and posted for public use at the Center for Engineering Strong Motion Data (CESMD) at strongmotioncenter.org.

To improve the rapid and accurate dissemination of strong-motion waveform data, the NSMP is currently undertaking a systematic review of the metadata and schematics associated with its structural instrumentation using teleseisms and regional earthquake recordings. Our approach uses filtered long period data from various large magnitude earthquakes around the world to enable the analyst to quickly discover where data channels within the structures deviate from the expected metadata database and identify potential sensor malfunctions. We outline this approach with examples of successful error identification using events such as: the March 4, 2021 Mw 7.3 earthquake near Gisborne, New Zealand; the July 8, 2021 Mw 6.0 Antelope Valley earthquake; and the November 28, 2021 Mw 7.5 earthquake near Barranca, Peru. This approach is particularly useful for highlighting cases where sensors may be oriented in the structure differently than described by metadata and seismic array schematics, so corrections can be made in advance of the next local triggering strong-motion event.

Uncertainty Quantification Over Spectral Estimation of Ground Motion Processes Subject to Missing Data Using Variational Bayesian Inference

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Power spectral density function (PSDF) plays an important role in the representation of stochastic processes including the characterization of ground motion processes or the modelling of engineering vibration and response processes. However, spectral estimation becomes challenging when only partial observations are available.

Many signal reconstruction methods fail to appropriately account for the inherent uncertainty associated with the problem of missing data. To estimate the uncertainty of PSDF for the ground motion stochastic process given incomplete recording, we propose a novel method where a Bayesian neural network is constructed to probabilistically capture the temporal patterns from time-series data. The Bayesian neural networks are specifically trained on simulated ground motions given the metadata of the incomplete recording (e.g. magnitude, epicentral distance, Vs30, etc.), as geological priors. This allows to complement the incomplete recording with additional information available about the physical phenomenon. More specifically, epistemic uncertainties on the model parameters of the Bayesian neural network model are learnt via Variational inference. Thanks to the probabilistic merit of the Bayesian neural network, an ensemble of reconstructed complete realizations can be obtained, which leads to a probabilistic power spectrum with each frequency component represented by a probability distribution, by standard spectral analyses. It is of great importance to researches such as stochastic structural dynamics, where accurate PSDF are needed for characterizing engineering excitation processes but faced with scarce and incomplete ground motion recordings.

Improving Strong-motion Data, Products and Services: From Waveform Quality to Open Dissemination

Poster Session · Wednesday 20 April · Conveners: Carlo Cauzzi, ORFEUS, SED, ETH Zurich (carlo.cauzzi@sed.ethz.ch); Hamid Haddadi, CGS-CSMIP & COSMOS (hamid.haddadi@conservation.ca.gov); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); Giovanni Lanzano, Istituto Nazionale di Geofisica e Vulcanologia (giovanni.lanzano@ingv.it); Lisa Schleicher, U.S. Geological Survey (lschleicher@usgs.gov); Olga-Joan Ktenidou, GEIN-NOA (olga.ktenidou@noa.gr); Jamison Steidl, University of California, Santa Barbara (steidl@ucsb.edu)

A DesignSafe Ground Motion Database

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This work presents a ground motion database for California and its close surroundings (i.e., areas near the border with Nevada, Oregon and Arizona) between 1999 and 2021 observed by 74 different networks and data centers. This DesignSafe ground motion database for California is hereafter referred to as the DSGM-CA and is available at DesignSafe-Ci. The DSGM-CA includes earthquakes with magnitudes larger than 3 and focal depths less than 40 km. Ground motion records and events included in this dataset are collected and processed using the gmprocess toolkit, which is an automated protocol developed by the USGS. Path measures such as rupture distance and epicentral distance are computed. Pseudo-Spectral accelerations, duration metrics, Arias intensity and other ground motion intensity measures are provided for records that pass the quality assurance (e.g., signal-to-noise check) check performed by the gmprocess toolkit. Additionally, site metadata are provided, including wave velocity information (from proxy-based time-averaged shear-wave velocity for the top 30 m, V_{s30}, and from P- and S- wave measured velocity profiles when available), predominant frequency measured from microtremor-based horizontal-to-vertical ratios and site-specific kappa0 values computed from multiple ground motions recorded at each station. 131651 ground motions observed from 1251 earthquakes are included in this database with distances ranging from 0.24 to 335 km, which are accessible via DesignSafe.

A Python-based Toolset for Identifying Strong-motion Earthquake Database Gaps

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The advancement of modern seismic monitoring equipment combined with near real-time seismic data acquisition and processing has increased waveform dataset availability in strong-motion data repositories. The U.S. Geological Survey National Strong Motion Project (NSMP) recently implemented its AQMS (ANSS Quake Monitoring System)/PRISM (Processing and Review Interface for Strong Motion) integrated system to acquire and process waveform data from networks in the US and internationally for distribution through the Center for Engineering Strong Motion Data (CESMD). In order to address limitations in processing time windows, data delays and improvements to the AQMS/PRISM system beginning in late 2018, as well as to backfill data for older events, we have developed a Python-based toolset for analyzing and visualizing gaps in US strong-motion event data at CESMD from the last decade. As an initial result, we discovered more than 1,000 missing events (California (and Nevada M ≥ 3.5, Alaska ≥ 6.0, other USA area M ≥ 5.0), including swarms associated with the 2018 eruptions of Kilauea and aftershocks of the 2018 M7.1 Anchorage, 2019 M7.1 Ridgecrest, 2020 M6.5 Monte Cristo Range and 2021 M6.0 Antelope Valley earthquakes. The preliminary analysis highlights the need to standardize data acquisition magnitude-distance thresholds. The toolset can be utilized as a postprocessing quality control tool to check for completeness of available records and identify failures in the automatic waveform processing due to station metadata inconsistencies as well as recovery of field data. Future work includes reprocessing events to fill data gaps at CESMD, expansion to international datasets and using data analytics and visualizations to develop further insights into the data and prioritize data gap recovery, especially at stations located in the near field of large earthquakes, on soil to expand records useful for site response and ground motion investigations and at instrumented structures.

Ground Motion Packet (GMP): A GeoJSON Specification for Ground Motion Metrics

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We present a specification for earthquake event-associated and unassociated ground motion metrics to facilitate data exchange, called a Ground Motion Packet (GMP). This ground motion metric format follows the GeoJSON (https://geojson.org/) standard. The primary goal of the format is efficient and extensible representation of ground motion metrics, in which we use the term "metrics" to refer to parametric data derived from ground motion waveforms (e.g., accelerograms, velocity recordings). Examples of commonly used metrics include peak ground acceleration (PGA), peak ground velocity (PGV) and spectral acceleration (SA). This format is designed so that it can also include metrics that are gaining popularity for many engineering use cases, such as significant duration, Arias intensity and inelastic response spectra. This format also supports the expanding list of methods that combine as-recorded channels in computing ground motion metrics. We expect that this format will be useful for many applications that compute or make use of ground motion metrics including, but not limited to, ShakeMap. The GMP format is not intended as a complete description of station metadata or site installation, although the format does include metadata that is necessary for most ground motion metric use-cases. The purpose of the metadata included in the GMP format is to provide high-level information regarding the suitability of the metrics for common engineering/seismological applications. The format also supports provenance information that follows the SEIS-PROV standard (http://seismicdata.github.io/SEIS-PROV/).

Güralp Data Centre Software for Easy Mass Data Acquisition and Station Metadata Monitoring

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Güralp Data Centre (GDC) interface offers 'one click' tools to configure instruments to stream data to a central (typically cloud based) server where it is saved in miniSEED in configurable folder structures. This application is particularly important for operators dealing with large volumes of seismic waveform data from regional/national networks. The GDC is particularly effective when coupled with low-latency streaming protocols, like Güralp's GDI-link: data is streamed from seismic stations to the GDC, which in turn efficiently forwards the data to the desired location, in the most appropriate format, reducing the overall latency of the system.

Additionally, the data can be transmitted to downstream processors such as Earthworm or SeisComP for more advanced seismic monitoring and data analysis. GDC has a simple interface to set up and monitor the operation of the network and is easy to implement into existing systems and networks with minimal configuration as industry standard protocols are employed throughout.

An integrated VPN/Tunnel circumvents Network Address Translations (NATs) present in internet modems and ADSL connections, providing the facility to remotely update digitizer firmware and upload configuration files to multiple units simultaneously.

Long term latency monitoring, network outages and bandwidth usage are captured and displayed in a number of applets that further simplify maintenance of large networks. The GDC dashboard allows network managers to view data integrity over time so that latency performance can be monitored.

Trigger events from instruments can be recorded and displayed on a map as part of a range of features dedicated to EEW implementations. This information is conveyed using the open Common Alert Protocol (CAP). The CAP messages are created by individual station or sub-network triggers and contain important parameters such the on-site recorded PGA, PGV and PGD, providing the lowest possible latency for network early warning.

Systematic Comparisons of Broad-band Velocity and Acceleration Earthquake Records as a Quality Assessment Tool for European Open Strong-motion Data

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Quality assessment of the data and metadata distributed by open earthquake databases is crucial in order to provide reliable information to seismology, engineering seismology, soil dynamics and earthquake engineering science and practice. The ORFEUS (Observatories and Research Facilities for European Seismology) community coordinates two major strong-motion seismology services (https://orfeus-eu.org/data/strong/) in the greater European region, i.e., the rapid raw strong-motion (RRSM) and the engineering strong-motion (ESM) databases and associated web interfaces and web services. ORFEUS data and services are routinely assessed and improved through the technical and scientific feedback of a User Advisory Group (UAG), which comprises European Earth scientists with expertise on a broad range of disciplines. Spurred by the suggestions of the ORFEUS UAG and of the ORFEUS user community at large, we are complementing the existing quality control procedures implemented in the RRSM and ESM with systematic and homogenous time- and frequency-domain comparisons of earthquake records from stations with co-located broad-band velocity and acceleration sensors (400+ contribute to the ESM and RRSM) as a quality assessment tool for European open strong-motion data. Among the goals of this study are: (i) detecting anomalies in both waveform data and station metadata (e.g., issues with gain, timing, orientation); (ii) refining automatic & manual waveform processing schemes (e.g., to improve identification of noise and clipped waveforms); (iii) enhancing usage of velocity records in 'strong-motion' databases like the ESM & RRSM (e.g., to tune/review low-frequency cut-offs). Initial selected results for stations in Greece, Italy, Portugal, Turkey and Switzerland are presented and discussed in this contribution. We aim at community feedback on the adopted strategy and the information obtained. This collaborative work is instrumental for the preparation of free and open-source software to perform systematic and on-demand analyses of the data from co-located instruments.

Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake

Oral Session · Thursday 21 April · 4:30 PM Pacific

Conveners: Jeffrey T. Freymueller, Michigan State University (freymuel@msu.edu); Julie Elliott, Michigan State University (julieelliott.ak@gmail.com); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Lucinda Leonard, University of Victoria (lleonard@uvic.ca); Natalia Ruppert, University of Alaska Fairbanks (naruppert@alaska.edu); Andrew Schaeffer, Geological Survey of Canada (andrew.schaeffer@canada.ca); Derek Schutt, Colorado State University (derek.schutt@colostate.edu); Rob C. Witter, U.S. Geological Survey (rwitter@usgs.gov)

Twenty Years of Intraplate Alaska Earthquakes Since the 2002 Denali Fault Earthquake

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The 2002 Denali fault earthquake occurred in the nascent era of broadband station coverage of regional seismic networks. Since that time, station coverage in mainland Alaska has expanded significantly, especially with the installation of the EarthScope Transportable Array starting in 2014. The expanded coverage has enabled improvements in: 1) rupture models for the largest earthquakes, 2) source mechanisms of moderate earthquakes and 3) seismicity characterization, owing to lower-magnitude and better-located events. We will provide an overview of non-plate-boundary earthquakes near mainland Alaska, including the 2016 Mw > 6 Kaktovik earthquakes and M > 7 Pacific plate events: 2016 Mw 7.1 Iniskin, 2018 M 7.9 offshore Kodiak, 2018 Mw 7.1 Anchorage. We will also examine source mechanisms for moderate earthquakes (Mw 3.5-5.0) across Alaska to gain insights into the active tectonic setting. At the smallest magnitude levels, there have been prolific swarms, such as in the northeastern Brooks Range and Purcell Mountains, for which the underlying processes are unknown. The EarthScope-era earthquake recordings in the western and northeastern Alaska provide a new frontier for understanding active tectonics, as well as for high-resolution seismic imaging.

New Look at the m7.9 2018 Offshore Kodiak Aftershock Sequence With the AACSE Ocean Bottom Broadband Deployment

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A magnitude 7.9 earthquake struck ~300 km offshore Kodiak Island in the outer rise region of the Alaska-Aleutian subduction zone on January 23, 2018. Prior to the earthquake, several fracture zones have been identified in the vicinity such as the Aja Fracture Zone. In addition, seismic reflection and high-resolution bathymetry have revealed numerous ~N-S trending faults, which were interpreted as pre-existing fractures in the Pacific Plate spreading fabric that have been reactivated as predominantly normal plate-bending faults by Pacific Plate subduction. While the moment tensor for the earthquake suggests predominantly strike-slip faulting, the true complexity of the source has only become evident through analysis of multiple datasets. Several studies combined analysis of the aftershock locations, seismic moment tensors, teleseismic P-wave back-projection and GPS displacements to constrain complex faulting during the M7.9 earthquake. All concluded that a complex system of conjugate strike-slip faults has been involved in the rupture, with possible dynamic triggering on some of the sub-faults.

Between May 2018 and September 2019 the Alaska Amphibious Community Seismic Experiment (AACSE) covered about 650 km along the segment of the subduction zone that included Kodiak Island. It comprised 75 ocean bottom seismometers and 30 land stations. In the fall of 2021, the AACSE regional earthquake catalog was released, including additional events and phase picks identified with the permanent and AACSE networks. This unprecedented dataset greatly enhanced the earthquake catalog by increasing the number of detected earthquakes and improving the accuracy of their source parameters. In the offshore Kodiak region, 50% more events were added to the catalog, with detection level down to magnitude 2, and ~60% more phase picks were also added. We will relocate the aftershock sequence using a three-dimensional velocity model and explore the effect of the velocity structure on the locations to minimize any resulting bias. This is essential for accurately determining the locations of the aftershocks relative to bathymetric features.

Subduction Megathrust Coupling in the Shumagin Gap Region Inferred From the 2020-2021 Earthquake Sequence

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Since 2020, three large magnitude earthquakes have occurred in the vicinity of the Shumagin Islands: the 22 July 2020 Mw 7.8 megathrust event, the 19 October 2020 Mw 7.6 intra-slab strike-slip event and the 29 July 2021 Mw 8.2 megathrust event. The 2020 events occurred in the transition from high plate interface coupling east of the Shumagin Islands to low coupling near the Shumagin Islands and reflect this transition. The 2021 Mw 8.2 megathrust earthquake occurred further to the east, rupturing a large part of the 10 November 1938 Mw 8.2 rupture zone. Slip models for the two megathrust events indicate adjacent ruptures (that may overlap), with peak slip of 3-4 meters in the 2020 event and 4-5 meters in the 2021 earthquake. However, while the 2020 aftershock sequence was very active, the 2021 earthquake had a relatively low level of aftershock activity. That—along with the co-seismic slip estimates—suggests that nearly all the slip deficit that could accumulate since 1938 (~5 m) was recovered in the mainshock. We find using finite element models of coupling in the subduction zone that if the Shumagin Gap region were strongly coupled, then the slip in the 2021 event would be ~2 m or less. In contrast, with an uncoupled Shumagin Gap, the maximum resulting slip magnitude in our models is 4-5 m, compatible with observations from the July 2021 earthquake. These results indicate that the 2021 megathrust event likely occurred adjacent to an uncoupled part of the megathrust (similar to the July 2020 megathrust earthquake but rupturing into the coupled part of the megathrust to the east), allowing nearly complete slip deficit recovery. Although the Shumagin Gap appears to be uncoupled, the coupling situation up-dip of the 2021 earthquake remains enigmatic. Like Cascadia, the lack of shallow plate interface aftershocks precludes the use of seismicity to infer coupling state. Using our modeling setup, we explore implications for scenarios with various degrees of coupling on the shallow plate interface.

Structure and Kinematics of the Eastern Denali Fault From Drone and Crewed Airborne Lidar Surveys

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The Eastern Denali fault (EDF) in the Yukon has not, until now, been widely covered by lidar data and previous interpretations of its kinematics and paleoseismic record based on remotely sensed data have been subject to considerable uncertainty. We present new lidar data collected with a rotary-wing drone and crewed fixed-wing aircraft over several segments of the EDF on the southwest side of Kluane Lake, which enabled the production of Digital Terrain Models (DTMs) with 30 and 100 cm spatial resolution respectively. These datasets offer a substantial increase in spatial resolution and canopy penetration compared to existing spaceborne and airborne photogrammetric Digital Surface Models (DSMs) of the EDF. Our mapping of the EDF identifies multiple locations where previous DSMs did not accurately portray the fault surface trace. The lidar data also provide improved estimates of fault offset and kinematics: stream channels and hill slopes that cross the fault at high angles indicate dextral offsets of 5–75 m. Vertical separation ranges from 0–20 m, varying between NE- and SW-side up. Offset across the fault varies considerably between geomorphological surfaces of different ages (i.e., glacial drift vs. younger fluvial terraces), suggesting that the lidar data may be able to distinguish multiple slip events. The higher spatial resolution achieved by the drone lidar reveals possible E-W-trending compressional structures (fault tips or fold axes) on a series of sediment mounds along the fault. These short-wavelength features are not visible in the coarser resolution crewed airborne lidar. Drone lidar is a relatively new technology, and this study allows for a comparison of the costs and benefits of drone versus crewed airborne lidar

acquisition for active tectonics research; the drone is less expensive to deploy and offers a substantial increase in point density, but covers a smaller area and is subject to several practical and regulatory constraints.

Queen Charlotte Plate Boundary: Insights From Earthquake Relocations and Seismic Tomography

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The 2012 Mw 7.8 Haida Gwaii earthquake near the southern end of the Queen Charlotte plate boundary was nearly pure thrust, whereas the 2013 Mw 7.5 Craig earthquake to the north was primarily strike-slip, highlighting the transition from oblique convergence to nearly pure transform along the margin as well as potential tsunami hazards. We apply an automated processing sequence of auto-regressive phase detection, onset estimation, phase association and hypocentral location to seismic waveform archives from temporary and permanent seismic arrays between 1998-2020. This study has produced a new automated earthquake catalog of ~47600 events each with at least 4 paired P and S picks in the region 50-57ºN and 126-136ºW, tripling the ~15000 previously known events from the Canadian National Seismic Network (CNSN). We use a combined (automated + CNSN) seismic catalog to invert for 3D velocity structure and relocate seismicity using double-difference seismic tomography. South of ~52.8ºN, seismicity is partitioned between the crustal transform, the inferred underthrusting Pacific Plate and "outer-rise" events seaward of the Queen Charlotte Terrace (QCT). The seismic activity in (1) the region seaward of the QCT and (2) the region south of ~52.5ºN along the strike of the crustal transform, is largely confined to the year following the 2012 Mw 7.8 earthquake such that, outside of this period, the regions represent seismic gaps. North of 52.8ºN, seismicity is temporally continuous and confined to the crustal transform. A right-stepping fault jog is suggested near 53.2ºN and associated with shallower seismicity (<10 km depth) to the north. Onshore, we identify seismicity between 14 and 18 km depth along a peculiar curved lineament at ~53ºN on northern Moresby Island in Aug-Dec 2013. We interpret these along-strike and across-strike variations in seismicity and velocity structure and discuss the implications for regional tectonics and local hazards.

Insights from Earthquakes in and Around Alaska in the 20 Years Since the Denali Fault Earthquake

Poster Session · Thursday 21 April · Conveners: Jeffrey T. Freymueller, Michigan State University (freymuel@msu.edu); Julie Elliott, Michigan State University (julieelliott.ak@gmail.com); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Lucinda Leonard, University of Victoria (lleonard@uvic.ca); Natalia Ruppert, University of Alaska Fairbanks (naruppert@alaska.edu); Andrew Schaeffer, Geological Survey of Canada (andrew.schaeffer@canada.ca); Derek Schutt, Colorado State University (derek.schutt@colostate.edu); Rob C. Witter, U.S. Geological Survey (rwitter@usgs.gov)

Aftershock Regions of Aleutian-Alaska Megathrust Earthquakes, 1938-2021

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Over the course of five earthquakes (1938, 1946, 1957, 1964, 1965), the Aleutian-Alaska subduction plate boundary ruptured over nearly all its 3551 km length. We revisit these five earthquakes-first studied in detail by Sykes (1971)-by relocating a catalog of carefully selected mainshocks and aftershocks. Our relocation method employs probabilistic estimation of hypocenter and origin time, while allowing for station errors estimated from total set of 538 events. Our final catalog of 324 events is established from a set of 12 mainshocks that includes all Mw >= 7.8 megathrust earthquakes and two relatively well-studied smaller events (1948-05-14 Ms 7.5, 1979-02-28 Mw 7.5). Using the relocated catalog, we create revised aftershock regions delimited both parallel and normal to the trench and exhibiting significant differences from previous studies. These aftershock regions provide information and constraint on coseismic slip extent, with the following basic findings: The 1938-11-10 Mw 8.3 earthquake extended further west, to the Shumagin Islands, and further east, into the Kodiak region, relative to the prevailing aftershock region established by McCann et al. (1979). The 1946-04-01 Mw 8.6 sequence was anomalously concentrated near the trench, which likely contributed to the exceptionally large tsunami. The 1957-03-09 Mw 8.6 aftershocks spanned a 1234 km length with numerous aftershocks within the outer-rise region of the incoming Pacific plate, where abundant normal-faulting continues to the present. The 1964-03-28 Mw 9.2 aftershocks extended east into the Pamplona thrust system (south of Icy Bay, Alaska), suggesting coseismic rupture into this region; this is consistent with coseismic static displacements, as well as current estimates of interseismic locking. The post-1965 events we examine are all smaller than the earlier events, but since they occurred in an era of improved data collection (seismic, geodetic, tsunami), they provide a better opportunity for assessing the link between the distribution of aftershocks and the occurrence of coseismic, postseismic and interseismic slip.

Along-strike Variation in Plate-bending Seismicity and Relationship to the Seismic Cycle in the Alaska Subduction Zone

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We investigate plate-bending earthquakes along the Alaska subduction zone using ocean bottom seismic data from the Alaska Amphibious Community Seismic Experiment (AACSE), as well as the EarthScope TA and other land-based seismic networks. We use seismicity data from the AACSE catalog, along with additional events detected using a machine-learning algorithm (EarthquakeTransformer). Events are relocated in a three-dimensional velocity model based on Rayleigh wave tomography. The incoming plate seaward of the Shumagin Gap is characterized by normal faulting and high seismicity, consistent with fault scarps observed in the bathymetry. These earthquakes extend from the surface to 35 km depth, peaking around 20 km depth. The depths of these earthquakes suggest that the upper 15 km of the mantle is partially serpentinized by water circulating along plate-bending faults. This indicates a large subducted water flux in the Shumagin region, consistent with structural studies of the region using active and passive techniques showing low upper mantle seismic velocities. Eastward, the seismicity rate is much lower in the Semidi and Kodiak regions and focal mechanisms are more diverse, including normal, strike-slip and reverse faulting events.

Variations in incoming plate faulting are highly linked to variations in megathrust earthquake properties and seismic hazards along the Alaska subduction zone. The subduction of water in fault zones in the Shumagin Gap may facilitate aseismic slip there. Increased interplate coupling in the Semidi and Kodiak regions may cause the more heterogeneous stress pattern in the incoming plate in those segments compared to the extensional stress in the Shumagin region. The absence of significant incoming plate normal faulting seismicity after the July 28, 2021 M_W 8.2 Chignik earthquake in the Semidi Segment suggests that the shallowest parts of the megathrust were locked during the earthquake rupture, consistent with source studies of that event.

Catalog of Coseismic Displacements Across Alaska

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A significant number of moderate to large earthquakes have occurred across Alaska over the last two decades, with each event causing permanent coseis-

mic and/or transient postseismic displacements over a large area. At the time of the 2002 Denali fault earthquake, there were very few continuous GNSS sites across Alaska, so most data for that event came from campaign surveys. The development of the Plate Boundary Observatory (now Network of the Americas, NOTA) starting in 2004 substantially increased the number of continuous sites, making it much easier to resolve the effects of these earthquakes through space and time. For example, the recent Simeonof (2020, MW7.8) and Chignik (2021, MW8.2) events on the subduction interface offshore the Alaska Peninsula caused detectable coseismic displacements as far north as the Seward Peninsula. Prior to the installation of NOTA, this deformation would not have been captured. Without a robust network of continuous GNSS sites along the Alaska Peninsula, it would have been extremely difficult to separate the coseismic and postseismic effects from the closely spaced Simeonof, 2020 M7.6 Sand Point and Chignik events. Capitalizing on the improved data resolution, we present a catalog of observed and model displacements from the most important earthquakes in Alaska over the last two decades.

Earthquakes, Interseismic Coupling and Stress Triggering Along the Eastern Alaska Subduction Margin

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During 2020-2021, an earthquake sequence consisting of an M7.8 and an M8.2 event ruptured within two neighboring segments of the Alaska-Aleutian subduction zone offshore of the Alaska Peninsula. This complex convergent system displays highly variable interseismic coupling as well as distinct changes in structural properties along the plate interface. The spatial and temporal proximity of the 2020-2021 events and their relation to previous events provide opportunities to investigate stress transfer and earthquake triggering, conditions required for rupture propagation and how structure and coupling may influence the location and size of earthquakes.

We present a coseismic slip model for the 2021 M8.2 Chignik earthquake constrained by static GNSS displacements, InSAR data and seismic and high-rate GNSS waveforms. The Chignik event originated at the northeast edge of the 2020 M7.8 Simeonof rupture zone and propagated to the northeast. Almost all of the rupture was within the Semidi segment of the megathrust while the Simeonof rupture largely stayed within the Shumagin segment to the west, with little significant overlap between the earthquakes. The boundary between the Shumagin and Semidi segments is defined by both structure and present-day geodetic coupling. The division of slip between the earthquakes suggests that these characteristics may influence earthquake rupture nucleation and arrest. Coulomb stress changes show that the Simeonof event brought the hypocentral region of the Chignik event closer to failure. A re-evaluation of the M8.3 1938 earthquake suggests that it could have brought the hypocentral region or area of major energy release of the Simeonof event closer to failure. Given these stress changes and the lack of significant overlap of rupture area between the 2020-2021 earthquakes and the new estimate of the 1938 earthquake, the events may be part of a megathrust cascade that has ruptured almost the entire margin over the past 80 years.

Estimating Vs30 in Anchorage, Alaska Using HVSR of Earthquakes vs. HVSR of Ambient Noise: A Comparison

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Anchorage, Alaska (USA) is situated within a deep, geologically complex sedimentary basin with significant spatial variability. Understanding ground motion characteristics and site response across this seismically active, populous region is critical; however, site-specific subsurface characterization is lacking at many of the strong-motion recording stations in the area. Previous studies have employed various methods to estimate the seismic characteristics of the Anchorage area. Recently, a regional model was developed between the time-averaged shear-wave velocity of the upper 30 m (VS30). The horizontal to vertical spectral ratio (HVSR) of earthquake ground motions, spectral amplification ratios and VS30 measurements were used to develop a contour map across Anchorage. Western Anchorage, however, is underlain by deep and complex soil deposits that, in some cases, have low shear wave velocities at depth and are not well-characterized by VS30. Here, we compare earthquake-based versus ambient noise-based HVSR and suggest improvements to the estimation of VS30 and provide recommendations for collection of ambient noise-based HVSR based on our observations and the variability of the complex geologic conditions found below Anchorage.

Potential Megathrust Co-seismic Slip During the Sand Point, Alaska Strike-slip Earthquake

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The 2020 M7.6 Sand Point, Alaska, Earthquake and its attendant tsunami have proven to be a peculiar event that highlights the limit of our knowledge with respect to tsunami sources of seismological origin. Of the sequence of recent earthquakes spanning the Shumagin and Semedi segments, it has produced the largest tsunami of the three. This work aims to understand this behavior.

We use two inversion approaches to understand the event. First, we used water level data and geodetic data to invert for sea surface deformation necessary to recreate the tsunami waveforms at tide gauges in Alaska and Hawaii, as well as with the Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys. We ran the inversion results in the tsunami modeling code, GeoClaw. We also perform a joint slip inversion for strike-slip and megathrust geometries.

We found that a strike-slip source alone is unable to recreate the tsunami waveforms at any of the tide gauges and DART buoys. The strike-slip tsunami sources were unable to match the amplitudes of the observed waveforms, being at best ~50% the size of the observed max amplitude of the waveforms and at worst not being able to recreate anything at all. We found that hydrodynamic method inversion results were able to mostly recreate the first arrival of the tsunami at the tide gauges and DART buoys and were able to recreate the wave packet behavior.

These results strongly suggest that a strike-slip earthquake alone is unable to be the sole cause of the Sand Point tsunami. The inversion scheme shows that co-seismic slip along the megathrust in addition to strike-slip co-seismic slip are needed to explain the event's tsunami. FInally, we find that a small submarine landslide in the western edge of the deforming region is likely needed to fully explain the tsunami waveform at King Cove, AK. The combination of megathrust co-seismic slip and strike-slip co-seismic slip puts the Sand Point earthquake between Mw 7.88-8.00.

Relocating the 2021 and 1938 Chignik Alaska Aftershock Sequences with Station Corrections from AACSE Array to Improve Rupture Area Estimates

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The 2021 M8.2 Chignik Alaska earthquake and its aftershock sequence raise questions about whether it is a repeat of the 1938 M8.3 event in the Semidi segment, the extent to which their rupture areas overlap, how either relate to seismically-imaged structures, and whether additional megathrust earthquakes in the region are possible. Accurate aftershock locations for these great earthquakes are key, as the 1938 rupture area is estimated from its recorded aftershocks. Like most subduction zone earthquakes, these sequences occurred offshore away from seismometers, so their geometry is uncertain. Fortunately, in 2018-19 an on and offshore experiment (AACSE) was conducted in this region, providing good control on seismicity location prior to 2021. We improve the rupture area estimates for the Chignik and 1938 sequences using well-located earthquakes from AACSE to calibrate travel times to stations recording during the 2021 and 1938 sequences and subsequently relocating them. Our approach is fourfold: (1) Gather regional station corrections using the AACSE seismometers in the Chignik rupture region. Though the array did not record the 2021 event, the AACSE catalog is used to collect corrections for regional stations that recorded the sequence. (2) Apply these corrections to the velocity model to relocate the Chignik sequence. Initial hypocenter relocations show little lateral change, with more significant depth variation. Initial relocated hypocenters remain 25-45 km deep, consistent with the working theory that the 2021 rupture did not reach the surface. (3) Retrieve teleseismic station corrections for the larger 2021 aftershocks prior to relocation of the 1938 rupture, which only has data from stations >30 degrees epicentrally. (4) Relocate the 1938 sequence using teleseismic corrections. There are too few recorded events in the 1938 sequence to unambiguously map the aftershock zone, but initial analysis suggests relocations to be similar to their original locations.

Seismic Velocity Structure Near 2020-2021 Major Earthquakes at the Alaska Peninsula

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Historical megathrust earthquakes ruptured in spatially separated segments along the Alaska Peninsula. Significant seismic and geodetic differences have been reported in the Shumagin and Semidi segments, such as background seismicity, large megathrust earthquakes, plate coupling and directions of the magnetic strips. In July 2020, an Mw 7.8 megathrust earthquake occurred in the Shumagin segment where it had not ruptured a great earthquake since at least the 1700s. Three months later in October 2020, an Mw 7.6 strike-slip earthquake occurred southwest of the Mw 7.8 event. It remains unclear why two large earthquakes with distinct focal mechanisms take place in the Shumagin Gap where the slab surface is dominantly creeping. In July 2021, an Mw 8.2 megathrust earthquake ruptured the Semidi segment, which was ruptured by an Mw 8.2 earthquake in 1938 and is characterized by moderate plate-coupling in recent years. Previous seismic studies have found along-strike changes in P-wave velocity of the subducted slab at the outer-rise region. However, it remains unclear whether there are structural differences in the Shumagin Gap and Semidi segment at depths around 30 km. In this study, we made use of the newly acquired seismic data from the Alaska Amphibious Community Seismic Experiment (AACSE), EarthScope USArray and the Alaska regional network. We imaged Vp and Vp/Vs structures in the Alaska Peninsula to 200 km depth using a double-difference tomography method. In our results, we find that the entire rupture area of the 2020 Mw 7.8 Simeonof earthquake is confined in a relatively high Vp/Vs region, where the 2021 Mw 8.2 Chignik earthquake rupture zone has higher and heterogenous Vp/Vs ratios. Interestingly, the 2020 Mw 7.6 strike-slip earthquake is located at a boundary between high Vp/Vs in the west and low Vp/Vs in the east. The spatial correlation of the Vp/Vs structure with the recent large rupture zones can shed light on the roles of slab properties in controlling megathrust earthquakes.

The 2020 M7.6 Sand Point Alaska Earthquake: Slip Model, Stress Change Contributions and Tsunami Implications

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On October 19, 2020 the M7.6 Sand Point strike-slip earthquake ruptured near the boundary between the Shumagin and Semidi segments of the Alaska-Aleutian megathrust at about 28 km depth. Thought to be an intra-slab event, the Sand Point earthquake is considered an aftershock of the July, 12 2020 M7.8 Simeonof megathrust earthquake that ruptured the deep part of the Shumagin seismic gap. An intriguing feature of the Sand Point event is the tsunami it generated, which is substantially larger than those produced by either the Simeonof event or the 2021 M8.2 Chignik earthquake; the latter ruptured the megathrust east of the Simeonof event.

Here we use high-rate GNSS and teleseismic waveforms, static GNSS offsets and InSAR observations to create a slip model for the Sand Point earthquake. We test scenarios that include only strike-slip faulting and others that also allow slip on the megathrust. Preliminary analysis suggests that coseismic GNSS offsets and teleseismic waveforms prefer a dominantly strike-slip scenario. Coulomb stress changes estimated for this scenario on the megathrust around the 2021 Chignik rupture zone are negligible, suggesting the Sand Point event did not significantly contribute to the timing of the 2021 Chignik event. We further compare observed tsunami waveforms to model predictions from various slip scenarios to investigate which coseismic model results in larger observed tsunami waveforms while maintaining a predominant strike-slip rupture mode and whether complex bathymetry or submarine landslides need to be invoked to explain the observed tsunami.

Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring

Oral Session · Thursday 21 April · 8:00 AM Pacific

Conveners: G. Eli Baker, Air Force Research Laboratory (g.eli.baker@gmail.com); John Patton, National Earthquake Information Center, U.S. Geological Survey (jpatton@usgs.gov); Josh Dickey, Air Force Technical Applications Center (joshuadickey@gmail.com); Ian McBrearty, Stanford University (imcbrear@stanford.edu); Jesse Williams, Global Technology Inc. (jwilliams@globaltechinc.com)

Deep-learning Seismology: Too Far, Too Close

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Seismology is a data-rich and data-driven science in which the application of machine learning (ML) techniques has been growing rapidly. Among variety of ML techniques, seismologists quickly recognized and realized the potential of deep neural networks (DNNs) to address a broad array of seismological applications. Much of this is due to the availability of large-scale datasets and the suitability of deep-learning techniques for seismic data processing; however, some aspects of applying AI to seismology are likely to prove instructive for the geosciences more broadly. Deep learning is a powerful approach but there are subtleties and nuances in its application. I will present a systematic overview of trends, challenges and opportunities in applications of deep-learning methods in seismology.

Post Hoc Visual Interpretation of Convolutional Neural Network Model for Earthquake Detection Using Feature Maps, Optimal Solutions and Relevance Values

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In recent years the seismological community is adopting deep learning (DL) models for many diverse tasks such as discrimination and classification of seismic events, earthquake detection and phase picking, earthquake early warning, etc. Many models have been developed and tested. However, it has been shown that their performances depend on the DL architecture, on the training hyperparameters and on the datasets that are used for training. To help the community to understand how final results and a model's performance depend on each of these different aspects, we propose implementing techniques that target the black-box nature of DL models. We apply 3 visualization techniques to a convolutional neural network (CNN) for the earthquake detection. The techniques are: feature map visualization, backward optimization and layer-wise relevance propagation methods, and help to answer questions: How is an earthquake represented within a CNN model? What is the optimal earthquake signal according to a CNN? Which parts of the earthquake signal are more relevant for the model to correctly classify an earthquake sample? These findings can help us understand how to build better model architectures, and also if there is a physical meaning embedded in a model from training samples. The CNN used in this study had been trained for detection on three-component waveform. Our analysis showed that the CNN model correctly identifies earthquakes within the sample window, while the position of the earthquake in the window is not explicitly given. The model handles earthquakes of different distance and magnitude values well, without having any physical information about them during the training process. The model constructs highly abstract latent space where different earthquakes can eventually fit. The interpretation techniques proved to be useful for having an insight of how the CNN model treats input samples, which is beneficial for understanding whether the architecture is well designed for this task.

A Collaborative Research and Development Program to Advance the Use of Machine Intelligence in Nuclear Explosion Monitoring

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The Air Force Research Laboratory (AFRL) initiated the Machine Intelligence for Nuclear Explosion Monitoring (MINEM) research and development (R&D) program in November 2020 with a five-year mandate to adopt machine intelligence in processing seismic and other geophysical signals to detect, locate and characterize seismic events. Automating these key processing tasks will benefit real-time monitoring operations for both earthquakes and nuclear tests.

The MINEM team includes data scientists and seismologists who are working together with AFRL and others in the U.S. Government to identify, evaluate and recommend techniques to fulfill R&D program goals. The MINEM program's first objective involved all team members working together to identify seismic explosion monitoring processes that are amenable to machine intelligence solutions and a variety of approaches to swiftly increase automated seismic event-processing capabilities.

Seven new MINEM R&D projects are addressing various monitoring needs, including a data-sharing platform and improvements to seismic phase onset-time determination, association, amplitude measurements and event location. In this presentation, we will discuss the broad scope of MINEM, active projects and future research opportunities, with the goal of soliciting increased participation from the research community to build an R&D program that delivers more capability to the U.S. Government.

Machine Learning Applications and Developments at the US Geological Survey's National Earthquake Information Center for Improved Regional-to-global Scale Monitoring

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The U.S. Geological Survey's (USGS) National Earthquake Information Center (NEIC) has a unique monitoring mission that spans local, regional and teleseismic scales. It fulfills its mission by processing waveform data streamed from an evolving inventory of thousands of globally distributed seismic stations. These stations represent a wide range of sensor types, interstation distances and noise characteristics. To utilize these waveform data, we implement specialized algorithms to derive a rapidly generated and accurate earthquake catalog. These algorithms must generalize across a global range of tectonic settings, recording environments, network configurations, data sampling rates, station quality, etc. Given these circumstances, machine learning (ML) techniques are particularly advantageous in improving the global monitoring capabilities of the NEIC.

In 2021, the NEIC operationalized a suite of machine learning models designed to improve automatic event association and location capabilities. These models improve pick-timing, classify phases and broadly estimate source-station distance which improves associator/location processing. Since the initiation of this project, NEIC has expanded its efforts to produce a reviewed global training dataset that can be leveraged to create new globally generalized teleseismic ML models. We recently created the Machine Learning Asset Aggregation of the Preliminary Determination of Epicenters (MLAAPDE) dataset and software to provide configurable and updatable training datasets tailored for specific ML-driven tasks.

We present the current state of the NEIC operational machine learning applications and the MLAAPDE dataset. Furthermore, we discuss our ongoing development efforts, including improving pick-timing estimates using analysts' specific models, and our efforts to create models that automatically indicate events that are not of response or cataloging interest to the NEIC. Lastly, we will highlight monitoring specific needs in ML applications, especially when considering their impact on real-time monitoring and the human driven review process.

Estimation of Hypocentral Parameters Based on Graph Neural Networks

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Seismic source characterization is both a necessity within the field of seismology and a requirement for further analysis such as hazard assessment. New machine learning (ML) models can directly analyze seismic data recorded from multiple stations of a seismic network using little preprocessing and no rule-based knowledge for this task. Most of them include convolutional neural networks which work well with array data, however, they require to give a predefined ordering to stations in the seismic network. Also, there is not an intrinsically way to incorporate spatial location of stations. An attempt to take advantage of spatial information consists in modeling the network as an edgeless graph, though, this approach considers that shareable information between nodes is not beneficial and omits graph neural networks (GNN) tools such as message passing. Therefore, there exists the question if the application of GNN framework can improve the performance of ML models.

In this work, we propose a GNN model that explicitly leverages the complex structure of Southern California Seismic Network for the task of estimation of hypocentral parameters (specifically, location and magnitude) of an earthquake, based on multi-station waveform recordings. Experiments show that using a simple GNN architecture, we can get some improvement over the results of recent studies.

Marsquake Detection With Deep Learning

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NASA's InSight seismometer has been recording Martian seismicity since early 2019, and to date, over 1200 marsquakes have been catalogued by the Marsquake Service (MQS) [1,2]. Due to their usually low signal-to-noise ratio (SNR), their detection and analysis remain challenging: the InSight background noise is characterized by extreme diurnal and seasonal amplitude variations and is strongly contaminated by transient and persistent signals which mainly originate from the interaction of the local environment with the various parts of the lander & seismometer system [3]. Conventional tools for automatic event detection, such as the STA/LTA algorithm, perform poorly on this dataset, as the various noise signals can have much higher amplitudes, often share a common bandwidth and can be similar in duration to marsquakes.

Machine learning tools are now routinely being applied to various complex seismological tasks. In this study, we use a deep convolutional neural network (CNN) designed for image segmentation [4] to detect marsquakes in a supervised approach. Based on the input—a time-frequency representation of the seismic data—the CNN is trained to predict a segmentation mask that identifies event and noise energy, allowing us to estimate the marsquake duration, frequency content and SNR. We use the CNN to automatically detect events and potentially remove their noise contamination [5]. To overcome the problem of the small training dataset, namely the low number of marsquakes with high SNR, we create synthetic events based on the different types of marsquakes [1] and combine them with recorded noise to include the various types of non-event signals. Here we present the results and compare the detection performance to the manually curated MQS event catalog [1,2].

[1] Clinton et al. (2021), 10.1016/j.pepi.2020.106595; [2] InSight Marsquake Service (2022), 10.12686/a14; [3] Ceylan et al. (2021), 10.1016/j.pepi.2020.106597; [4] Ronneberger et al. (2015), 10.1007/978-3-319-24574-4_28; [5] Zhu et al. (2019), 10.1109/TGRS.2019.2926772

FastMapSVM: Classifying Seismograms Using the Fastmap Algorithm and Support Vector Machines

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We present FastMapSVM—a new machine-learning (ML) framework for classifying abstract objects—in the context of classifying seismograms.

FastMapSVM classifies seismograms with accuracy comparable to leading Artificial Neural Network models, but needs only a small fraction of the training data required by those models and offers many additional advantages: FastMapSVM (a) can incorporate domain-specific knowledge into the classification task via a user-defined distance function; (b) explicitly compares test seismograms against representative reference seismograms in the original data domain during classification and (c) can be rapidly retrained to perform sundry classification tasks.

As the name suggests, FastMapSVM comprises two basic components. First, the FastMap algorithm (Faloutsos & Lin, 1995) maps abstract objects—seismograms in the present application—to points in Euclidean space such that the Euclidean distance between object images approximates a user-defined distance function that quantifies the dissimilarity between any pair of objects. Second, a Support Vector Machine (SVM) uses these Euclidean images to classify objects. Our novel combination of these two components in a classification framework promises to reduce the computational and data resources required to deploy ML models for specific applications. The reduction in the amount of training data required is particularly advantageous for applications with temporary stations or where training data is otherwise sparse.

Using only 16,384 training waveforms from the Stanford Earthquke Data Set (STEAD), we train FastMapSVM in 7.5 minutes and classify the remaining ~1.48M STEAD waveforms as either "noise" or "earthquake" with >97% accuracy in ~2.5 hours on a 64-core machine. We will present further details on FastMapSVM methodology and test results at the meeting.

Faloutsos, C. and Lin, K.I., 1995, FastMap: A fast algorithm for indexing, data-mining and visualization of traditional and multimedia datasets. ACM SIGMOD (pp. 163-174).

Assessing the Limits of Predictive Uncertainty in Seismic Event Discrimination Using Bayesian Neural Networks

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While Neural Networks have proven to be a powerful tool in the area of seismology, a recurring problem is the potential overconfident predictions generated by models on low quality or even unseen samples. Bayesian Neural Networks provide and approach to uncertainty estimation within deep learning models and are becoming increasingly tractable with developing computational and sampling paradigms. In this work we focus on an initial exploration of the performance of Bayesian Neural Networks for problems at scale, specifically seismic event type discrimination using both a 2D mapping and convolved features of seismic waveform spectrograms. We test different strategies to train a neural network within a Bayesian framework and examine the fidelity and usefulness of the predictive confidence with respect to decision-making by human analysts. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Towards a Dynamic Multi-net Approach for Earthquake Association

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Earthquake phase association is a crucial step in seismic data processing pipelines. It is becoming more challenging as more phases are detected due to the improvement of instrument sensitivities and increase of network coverage. Novel data-driven association techniques have shown promising results for large amounts of local and regional earthquakes. However, the applicability of these data-driven methods on sparse global-scale networks is still unclear. Using a 17-year (2000 - 2016) subset of the ISC Bulletin catalog that contains P phases of events between magnitude 5.5 and 6.5, we developed an association technique named the dynamic multi-net associator (DMA). The DMA consists of two main components: a network sampler and a dense neural network (DNN) locator. The network sampler subsamples seismic stations and generates feature inputs for the locator. The locator then predicts event locations and origin time for each of the subsampled networks (subnets). The solution of association is then determined based on the degree of consensus of the predictions among the subnets. To make the associator general to the global distant range, we constrain relative locations (great-arc distance R, back-azimuth B), and travel time (T) between events and an anchor station in each subnet. These parameters are constrained using differential features (dR, dB, dT) between the anchor station and the other stations. After trained on ~2 millions samples with subnets of 5 stations, the locator achieves good performance with one standard deviation error at ~3° for back azimuth, 5.73° for great-arc distance and 45.7 seconds for origin time. We plan to incorporate more physical features, such as relative amplitudes, energy decay, in conjunction with waveform embeddings generated by autoencoders to further improve the location accuracy. We will then conduct experiments on searching the optimal consensus thresholds to use for event association.

Measures for Evaluating Neural Phase Pickers on Continuous Waveform Data

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Recent studies showed the potential of neural phase pickers for reducing manual workload for earthquake catalog development; however, deciding on which model to deploy requires better evaluation metrics than many currently be available. The common approach of evaluating a trained model with a test dataset, which is often sampled from the same population that the training dataset was sampled from, has limitations for this task. Evaluation metrics may not represent the true performance of the model that we would observe after deployment as we may find many more earthquakes with magnitudes that are smaller than those in the test dataset and the data stream will be dominated by negative examples, i.e., non-earthquake signals. Waveforms in the test dataset can also be highly correlated with those in the training dataset, which can overestimate performance. One approach for circumventing these issues is to test the model on continuous waveform data from a well-recorded seismic sequence. With good station coverage and sufficient earthquake templates, we can build a template matching catalog and use that as a benchmark for evaluating a model by comparing it with the earthquake catalog developed from the model. We introduce approaches for counting true positive, false negative and false positive phase picks, as well as metrics for evaluating prediction consistency, phase confusion and the overall quality of the earthquake catalog developed from the model. We test the approach on the early stages of the 2019 Ridgecrest earthquake sequence.

Machine Learning Techniques for Sparse Regional and Teleseismic Monitoring

Poster Session · Thursday 21 April · Conveners: G. Eli Baker, Air Force Research Laboratory (g.eli.baker@gmail.com); John Patton, National Earthquake Information Center, U.S. Geological Survey (jpatton@usgs.gov); Josh Dickey, Air Force Technical Applications Center (joshuadickey@gmail.com); Ian McBrearty, Stanford University (imcbrear@stanford.edu); Jesse Williams, Global Technology Inc. (jwilliams@globaltechinc.com)

Analysis of the 2020 Albanian Durres Aftershock Sequence, Benchmarking Machine Learning Approaches

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In recent years, significant advancements have been made in automatically detecting seismic arrivals, driven by novel applications of machine learning routines to the problem of seismic event detection. For future seismic hazard mitigation, accurate, high-resolution mapping of active faults are crucial components in enhancing understanding of the stress field for any given region. The latest advancements in machine learning can potentially provide such insights. The November 26th, Mw6.4 Albanian earthquake, occurring ~30km North of Tirana was the deadliest earthquake of 2019, rupturing a portion of the Adriatic-Eurasia continental collision zone. We deployed a dense network of 30 temporary seismic stations to record the aftershock sequence in the immediate period following the mainshock.

To quantify the advancements in the latest automated event detection routines, we benchmark 2 of the latest machine learning-based event detection pipelines against the traditional 'state-of-the-art' analysis of human experts in detecting and analyzing the seismicity of the aftershock sequence. We apply the EQTransformer deep learning picker and built-in associator, along with the PhaseNet deep learning picker and Hyperbolic Event eXtractor (HEX) association algorithm to detect events in an 18-day period following the mainshock. These automatic event detection routines are benchmarked against a combined catalog of 220 events manually picked and located by two seismic experts. The PhaseNet & HEX and EQTransformer pipelines detect 3,551 and 1,110 total events during this period, detecting 99% and 94% of the manual events, respectively. We apply the PhaseNet & HEX automatic event detection routine to process the full 9 months of continuous data following the mainshock, detecting 19,152 events.

The resulting earthquake locations are used in deriving a new minimum 1D velocity model for the Albania region. We find that the aftershock seismicity clusters along faulting structures related to the deep seismogenic frontal detachment fault at a depth of 10 - 22 km and the shallow back-thrusting Vore fault at 2 - 4 km depth.

Automated Real-time Earthquake Energy Discriminator of Deep Earthquakes: A Comparison of Conventional and Ml Methods

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Rapid and robust identification of deep earthquakes is useful in the application of more accurate real-time analysis, location and warning, particularly at teleseismic distances where real-time estimates of depth can differ from reviewed calculations by up to tens of kilometers. In Barama and Newman (2018), we developed a method using the first-derivative of the per-station energy time series of earthquakes to identify distinct double-peaks of energy associated with the direct-P phase followed by the energy of the depth phases (pP and sP). This was a promising result from automatic processing of initial energy pulses without any additional processing of the waveforms and allowed Barama and Newman (2021) to apply machine Learning (ML) to deep earthquake detection using a Convolution Neural Network (CNN) trained on both physical features of the energy time series (prominence and peak density) as well as the original waveform. Initial results showed improved results on utilizing the time series and interestingly the peak-density per event time series over the first derivative per-station energy, despite the peak density curves having significantly less training data. In this work we continue testing and complete comparison of the conventional and new ML methods for rapid depth determinations with the inclusion of the smoothed and stacked energy rate determinations per event. Using over 2000 earthquakes (> 70km depth) that occurred between 1989-2019 with moment magnitude greater than 5.5 from the Reviewed International Seismological Centre (ISC) bulletin, we calculated the per-station energy flux (of the P-wave group energy) in the frequency domain. We set a threshold for deep event detection based on time differential between energy peaks in the smoothed energy rate determinations as well as training several CNN models to identify the usefulness of the derivative products over the event time series. We hope to implement these results in the real-time energy determinations operating at Georgia Tech (http://geophysics.eas.gatech.edu/anewman/research/RTerg/).

Deep Learning Seismic Signal Detection on the International Monitoring System

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Producing a complete and accurate set of signal detections is essential for automatically building and characterizing seismic events of interest for nuclear explosion monitoring. Signal detection algorithms have been an area of research for decades, but they still produce large quantities of false detections and fail to detect some of the real signals that must be detected to produce a complete global catalog of events of interest. Deep learning methods have shown promising capabilities in effectively detecting seismic signals with better recall and precision than traditional methods, but most applications have been to data recorded at local to near-regional distances. However, for nuclear explosion monitoring, we would like to use the method at all monitoring distances from local to teleseismic. In this study, we trained the Stanford-developed PhaseNet deep learning signal detection model with three-component station data from the International Monitoring System (IMS) and compare the results to the International Data Centre's Late Event Bulletin (LEB). To increase our training set size, we applied multiple filter bands to each LEB arrival and presented these differently filtered waveforms as separate samples to PhaseNet. Our training set consists of approximately 1,000,000 P phase samples and 200,000 S phase samples from 51 stations. Preliminary results show PhaseNet achieves 90% precision and recall on P phase detection/identification and 60% precision and recall on S phase detection/classification.

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SAND2022-0312 A

Expansion and Transferability of Seismic Deep CNN Denoiser to Global Networks

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Seismic noise from a variety of nuisance sources frequently contaminates signals of interest. Effectively suppressing this noise is a crucial step in the processing pipeline that frequently affects the quality of downstream products. Previous work by Tibi et al. (2021) developed a seismic signal denoising approach that uses a deep convolutional neural network (CNN) model to decompose a vertical-component input waveform into a signal of intertest and noise. While effective, this model was limited in that it was trained on regional data from Utah and only using data from the vertical component. In this study, we evaluate the transferability of the CNN model to other regions globally using data from the International Monitoring System (IMS) seismic station network. To train and test the CNN denoiser, we curate high-quality pure signal and pure noise datasets of seismograms recorded by stations in the IMS network and use them to construct >100,000 signal + noise waveforms. Results from applying the CNN denoising model are then compared with traditional frequency filtering as well as more novel denoising techniques, such as a continuous wavelet transform thresholding. Finally, we extend the current methodology to three components, resulting in a denoising model that is applicable to three-component data streams. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Using Machine Learning to Improve Pacific Northwest Earthquake Catalog

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Geohazards hazards in the Pacific Northwest are complex given the geodynamic environment. The seismic data from the PNW is particularly rich in the diversity of its sources (from earthquakes, landslides, volcanoes) and the complexity of the noise sources (anthropogenic, surface processes such as river and tree noise, variable microseismic signals) that contaminate the tectonic signals. The Pacific Northwest Seismic Network has been operating since 1969, providing us with an unprecedented period of time for data analysis. We complement that archive with temporary arrays (offshore and onshore) and permanent networks in Canada. The total archive reflects a rapid expansion of seismic networks and an increasing difficulty in collecting, storing, and analyzing seismic archives.

Machine learning has been promoted as an essential approach to processing such an enormous dataset and various seismic tasks. This research applies recent machine learning models to 20 years of the data archive. We use the SeisBench platform (Woollam et al., 2021) to apply various models (DeepDenoiser (Zhu et al., 2019), WaveDecompNet (Yin et al., 2022), PhaseNet (Zhu & Beroza, 2018), EqTransformer (Mousavi et al., 2020)) to the new data. Several modules are retrained using the PNSN earthquake and phase pick data, then we predict all remaining data available in the PNW. We establish uncertainties in the phase picks based on ensemble predictions and over various frequency bands.

Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information

Oral Session · Wednesday 20 April · 4:30 PM Pacific

Conveners: David J. Wald, U.S. Geological Survey (wald@usgs.gov); Heidi Stenner, Geohazards International (stenner@geohaz.org); Eric Fielding, NASA Jet Propulsion Laboratory (eric.j.fielding@jpl.nasa.gov); Haeyoung Noh, Stanford University (noh@stanford.edu); Susu Xu, SUNY Stonybrook (susu.xu@stonybrook.edu); Kate E. Allstadt, U.S. Geological Survey (kallstadt@usgs.gov)

Enhanced Rapid Earthquake Ground Failure and Impact Estimates With Remotely Sensed and Ground Truth Constraints

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Estimating earthquake impacts using physical or empirical models is challenging because the main components of loss estimation—namely shaking, exposure and vulnerabilities—entail inherent uncertainties. Loss modeling in near-real-time adds additional challenges, yet expectations for actionable information with a reasonable level of confidence in the results are real. Fortunately, advancements in remote sensing, rapid in-situ impact reporting and machine learning—combined with new datasets such as global building footprints—will allow for innovative data-fusion strategies that integrate with existing models and should greatly improve the accuracy and spatial resolution of rapid shaking and loss estimates. We are exploring two approaches.

First, early reports of casualties are used in a Bayesian updating fashion to constrain the possible range of fatalities and lower the prior models' uncertainties (see Engler et al., this meeting). Second, in the form of Damage Proxy Maps, remotely sensed satellite radar data are used in a Bayesian causal graph framework combined with machine learning to optimize the mapping among the physical processes that cause shaking-based building damage, landslides and liquefaction to prior expectation models. The casual graph framework also affords the potential for removing anthropogenetic noise contained in the imagery. Our main findings to date are that (1) updating the PAGER fatality model can prevent cases where PAGER losses are initially significantly off (e.g., the incorrect alert level) by quickly allowing updates, and that (2) the imagery—while slower than ground-truth observations—provide more spatially accurate impact assessments, well beyond the capabilities of the generalized loss and ground failure models. Ultimately, our two-fold model updating strategy will accommodate key ground-truth observations such as fatality reports, locations of building damage and ground failure reports to converge on actual losses more rapidly.

Local-international Collaboration Following the 2021 Haiti Earthquake for Rapid Building Damage Data Collection and Public Awareness Messaging

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Collaborations between local teams in Haiti and international researchers working remotely led to an efficient hybrid model for rapid data collection that provided open building damage data to the humanitarian community, as well as widely disseminated safety messages about aftershocks. These efforts demonstrate the effectiveness of local-international collaborative models in challenging post-earthquake operational contexts. This project leveraged a hybrid response model in which Haitian data collectors use a mobile app to acquire images and basic data on local buildings. Records are synchronized to the cloud where international volunteer virtual assessors later assign a damage rating and classify the structural system. The model was ultimately deployed across the Sud, Nippes and Grand'Anse departments by University of Notre Dame and nonprofit organization GeoHazards International (GHI) with funding from the U.S. Geological Survey (USGS) and the US Agency for International Development (USAID) and included the addition of a Haitian Creole version of the USGS Did You Feel It? survey in a mobile app to obtain data for future development of macroseismic intensities. This effort produced 12,699 building records and 2,163 Did You Feel It? surveys within 10 weeks of the earthquake. The dataset and technical resources were made freely available to the humanitarian community and can be viewed at https://www.steer.network/haiti-response.

USGS and GHI collaborated to develop Haitian Creole and English messaging about aftershocks, including guidance on staying safe. Messaging was developed using wording from the domestic USGS aftershock forecast template combined with protective action messages developed by GHI in a prior project. Messages received several rounds of informal reviews, with two Haitian translators ensuring correct use of Haitian Creole and message efficacy, among others. These messages were disseminated in both languages on USGS's main website page, the earthquake event website and Twitter feed and by GHI staff members in Haiti through local awareness campaigns.

NASA Urgent Response Products for the 2021 Mw 7.2 Earthquake in Haiti

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The 14 August 2021 Mw 7.2 earthquake in southwest Haiti caused extensive damage, which was compounded several days later when a tropical storm hit the same area. The NASA Applied Sciences Disasters Program activated a response to the disaster in cooperation with other organizations. We generated early response products from optical and radar satellite imagery, including surface displacement maps, Damage Proxy Maps (DPMs) and landslide distributions. The first high-resolution satellite images available for the area were from the Planet optical satellite constellation and the Copernicus Sentinel-1 synthetic aperture radar (SAR) satellites. Additional SAR data from JAXA ALOS-2 and Sentinel-1 and additional optical imagery was acquired later. We provided a series of products to characterize landslide impacts in the immediate aftermath of the event. High-resolution, low-latency Planet data was exploited to generate landslide inventories in the Pic Macaya national park within 24 hours of the earthquake. Experimental SAR-based landslide density estimates were also generated from Sentinel-1 amplitude images in Google Earth Engine across the entire area as a rapid way to establish areas affected by landslides even while cloud cover obscured optical mapping approaches. The surface displacement maps and DPMs were also calculated from the Sentinel-1 SAR with interferometric analysis. The surface displacement maps showed the fault rupture extended far to the west from the epicenter, consistent with the landslides in that area.

We used both ad-hoc email chains and the NASA Disasters Mapping Portal to provide urgent response products to stakeholders and other responding groups in a variety of locations. We received a few requests directly from stakeholders working with colleagues inside Haiti and provided products that way. The Mapping Portal provided an open interface to view and download data products through web browsers. A few products had licensing restrictions on due to the data sources and had to be provided only to a subset of groups.

Best Practices for Collecting and Using Post-earthquake Damage Data: Lessons From Haiti and Other Past Events

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Researchers often state that "perishable" data need to be collected after a disaster occurs, often referencing the collection of accurate damage information before repairs begin. Damage data, however, are perishable in a different way—they are collected, but they perish due to lack of use during an event. In this study, we review the multitudes of damage data sources available—and their potential uses—at different time points after an earthquake occurs. We then ask, have these various data sources been applied to these use cases after past events? Here, we focus on the acquisition and use of damage data after the 2021 Haiti earthquake, compared to four previous events, including Haiti's penultimate earthquake in 2010.

As a community of damage information providers, we find that we are moving in the right direction so that the damage data we acquire can simultaneously serve multiple purposes, both scientific understanding and post-event response and recovery planning. However, some use cases are rarely informed by damage data (urban search and rescue) while other use cases are over-represented (scientific understanding). Notably, certain damage data sources (rapid forecasts or recovery-oriented field surveys) consistently inform local planning while others do not. Based on this study and personal experiences, we close with a set of recommendations and best practices for future post-disaster data collection.

Improving the USGS Pager System's Reported Fatality Updating Framework

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The U.S. Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) system has provided near-real time estimates of fatalities and economic losses for significant global earthquakes since its inception in 2010. The PAGER system traditionally relied only on changes to earthquake ground shaking estimates for its alert updating, but recently we devised a method to improve the PAGER fatality estimates given reported losses using a recursive Bayesian framework (Noh et al., 2020). Having applied this framework to numerous recent deadly earthquakes, we discuss the key lessons learned. While the fatality updating framework has dramatically improved estimates of overall fatality distributions and accuracy of alerts, several key limitations associated with reported losses' timeliness and their uncertainties were identified.

This presentation summarizes our ongoing research to overcome these limitations, ensuring that the updated fatality estimates are statistically consistent and accurately considering associated uncertainties, and that the framework can be applied to a greater variety of both fatal and nonfatal earthquakes. The efforts include: (1) properly defining the loss projection model (a function describing how reported losses change over time) and accounting for both its epistemic uncertainty and correlation associated with reported losses, (2) allowing for updating to occur for earthquakes with no reported fatalities (but nonzero PAGER estimates) by determining when no reported fatalities qualifies as data, (3) allowing for updating when the reported fatalities do not change over a considerable period of time (i.e., determining when no change in fatalities qualifies as data) and (4) quantifying and incorporating additional uncertainties in the updating process. These developments represent a crucial step towards implementing the updating framework within the USGS National Earthquake Information Center's operational setting.

Modeling, Collecting and Communicating Post-earthquake Hazard and Impact Information

Poster Session · Wednesday 20 April · Conveners: David J. Wald, U.S. Geological Survey (wald@usgs.gov); Heidi Stenner, Geohazards International (stenner@geohaz.org); Eric Fielding, NASA Jet Propulsion Laboratory (eric.j.fielding@jpl.nasa.gov); Haeyoung Noh, Stanford University (noh@stanford.edu); Susu Xu, SUNY Stonybrook (susu.xu@stonybrook.edu); Kate E. Allstadt, U.S. Geological Survey (kallstadt@usgs.gov)

A Feature-based Liquefaction Image Dataset for Assessing Liquefaction Extent and Impact

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In the aftermath of an earthquake, data collection is an important part of the response and is used for both loss assessment and data curation for model development. For liquefaction impacts, post-earthquake data collection often relies on field investigations, which are usually spatially limited and incomplete. Field investigations may capture liquefaction spatial extent and resulting deformations, but not consistently. With the increased availability of high-resolution optical imagery and radar technologies like Synthetic Aperture Radar (SAR), researchers in recent years have employed a combination of field surveys and visual and automated mapping of liquefaction surface effects using remotely sensed data sources. The inconsistencies in how the field investigations and remotely sensed observations are mapped can impede liquefaction inventory development, in part due to the range in size of liquefaction features (cm's to 10s of m's) and the inconsistency of feature attributes. Prior liquefaction inventories are point-based and summarize liquefaction occurrence across a site (10s of m) as a single point and as a binary variable: liquefaction occurrence vs. non-occurrence. Visual assessment of surface effects and detailed spatial mapping demonstrate that not all liquefaction features are equivalent and liquefaction inventories would benefit from a measure of size as well as deformation. In this study, we provide a liquefaction image library that includes spatial polygons and labels for over 2000 liquefaction features with information such as the infrastructure impacted and the size of the features across multiple events: including significant liquefaction events such as Christchurch (2011) and Tohoku (2011), as well as minor liquefaction events such as Haiti (2010) and Puerto Rico (2020). Our study proposes a methodology and establishes an image-based liquefaction inventory using remotely sensed data like optical and SAR imagery that not only provides occurrence and non-occurrence labels, but also provides information on impact in terms of feature size, impacted infrastructure and deformation.

Advancing Real-time Tsunami Warning and Response: From Characterizing the Hazard Using GNSS to Estimating Loss Models

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Application of Global Navigation Satellite Systems (GNSS) to characterize large earthquakes is a viable tool for rapid estimation of the tsunami hazard along local coastal communities. Effort to leverage developed geodetic algorithms and techniques to modernize tsunami warning operations is being supported by the NASA Disasters Program. A major component of this project has been testing the Geodetic First Approximation of Size and Time (GFAST) algorithm on a suite of synthetic megathrust scenarios (fakequakes) in the Cascadia subduction zone. Results showcase the promise of estimating tsunami amplitudes along the coast driven by geodetic earthquake rupture models. Recent work also includes modeling the tsunami inundation in coastal areas along Cascadia from the megathrust scenarios and GFAST models. We are motivated to advance tsunami risk reduction by exploring the combination of rapid inundation modeling and loss estimation. The approach to rapid inundation modeling informed by GNSS constrained earthquake models provides a framework for projecting real-time tsunami losses and impact. We partner with experts in loss modeling and risk assessment from ImageCat to develop a tsunami loss estimation working group. Tsunami inundation modeling is focused on testing scenarios in the coastal Washington area using complex rupture scenario sources. Casualty modeling is explored and includes information on walking travel time and evacuation time scenarios. Approaches to probabilistic modeling using the Robust Simulation approach is also explored.

Towards Developing and Implementing an International Macroseismic Scale (IMS) for Earthquake Engineering, Earthquake Science and Rapid Damage Assessment

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Macroseismic data are valuable for post-earthquake situational awareness and geospatial shaking (e.g., ShakeMap) and damage analyses. Although popular systems like the USGS "Did You Feel It" enable community members to contribute abundant observations, two limitations remain: (1) lack of uniformity of data collection globally and (2) properly assigning higher (damaging) level intensities, for which untrained observers do not have the needed engineering expertise. We will start to address both concerns collaboratively via workshops held at the USGS Powell Center in the Fall of 2022. In terms of data uniformity, we aim to help harmonize the use of both internet- and field-based approaches in service globally with best practices, yet also by characterizing each's uncertainties when used quantitatively—consistent with the 2021 findings of the European Seismological Commission Working Group on Harmonizing Macroseismology. For higher intensities, alternatives to crowd-sourced observations are necessary, specifically, field-based engineering assessments. Yet, the need for professionals to make higher intensity assignments conflicts with rapidly and automatically assigning them. So, we aim for better approaches for such assignments by tapping into existing post-earthquake building tagging protocols such that engineers effectively assign intensities as a byproduct of their inspections.

Further, the Modified Mercalli Intensity (MMI) scale is outmoded compared to the European Macroseismic Scale (EMS-98), which quantitatively accounts for building vulnerability classes and damage levels. As such, we aim to revise the higher MMI levels in the US and New Zealand (NZ) to be compatible with EMS-98 by assigning missing US and NZ building vulnerability classes and damage grade descriptors. Lastly, we aim to make recommendations to implement these strategies in an update of EMS-98—applicable to the globe—which could become an *International Macroseismic Scale (IMS).*

Updating Liquefaction Probability Given Liquefaction Potential Index in a Bayesian Framework

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The U.S. Geological Survey's (USGS) ground failure (GF) product has been used since 2018 to estimate the extent of landslides and liquefaction following earthquakes in a near-real-time setting. Our goal is to improve the accuracy of the models that form the basis of the product by incorporating geological and geotechnical information when available regionally. The current models in the GF product are developed at a global scale whereas the inclusion of geological and geotechnical information (consisting of subsurface soil measurements) is only possible at regional scales and may not be consistent from region to region in terms of definition and availability. In this study, we focus on the model of liquefaction surface effects (LSE). One method to incorporate geotechnical data is via the liquefaction potential index (LPI) combined with a fragility function that predicts LSE from LPI. For a given ground shaking scenario, LPI can be used to estimate the probability of LSE using a lognormal cumulative distribution function. Within a Bayesian framework, we propose to use the global-scale model to compute the prior distribution of LSE probabilities and the LPI-derived LSE probability distribution as the likelihood function to compute the posterior distribution of LSE probability at a given site location. Uncertainty in estimating the LPI at a given location (potentially via correlations with surface geology) can be included in this framework. We demonstrate this updating process for assumed prior distributions and LPI values, illustrating the sensitivity of the posterior distribution to the inputs. We discuss implementation challenges and assumptions, such as the characterization of distribution assumptions necessary in this Bayesian framework, and approaches to estimating the likelihood function for the extent and resolution necessary for the USGS GF product. We also discuss potential parallel approaches for updating the landslide model with regional susceptibility data.

Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation

Oral Session · Friday 22 April · 2:00 PM Pacific

Conveners: Kenny Ryan, Air Force Research Laboratory (0k.ryan0@gmail.com); Roby Douilly, University of California, Riverside (roby.douilly@ucr.edu); Christodoulos Kyriakopoulos, University of Memphis (ckyrkpls@memphis.edu); Eric L. Geist, U.S. Geological Survey (egeist@usgs.gov); Ruth Harris, U.S. Geological Survey (harris@usgs.gov); David D. Oglesby, University of California, Riverside (david.oglesby@ucr.edu)

Kinematic Rupture Models of Listric Normal Faulting in Earthquake Ground Motion Simulations

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We investigated the performance of kinematic rupture models and effects of rupture characteristics on simulated ground motion from scenario earthquakes on the Yucca fault. The Yucca Fault is a listric fault that crosses a large portion of the Nevada National Security Site. Its unknown geometry at depth has a direct consequence in earthquake ground motion uncertainty estimates. In addition, the combined effects of the complex geometry of listric faults and normal faulting on earthquake near-fault ground motion are not well known. Using several rupture realizations representing different fault curvatures and rupture initiations, we conducted deterministic broad-band simulations (0-5Hz) and estimated ground motion characteristics in the Yucca Flat basin from M6.5 scenario earthquakes on the Yucca Fault. The simulations were performed on high performance computers using a 3D wave propagation finite-difference method and a seismic velocity model based on the geological framework model of the site. We used the Graves-Pitarka method to generate kinematic rupture models of normal faulting and a draping procedure to adjust the simulated spatial slip distribution to curved listric fault surfaces. Simulation results obtained for 16 rupture scenarios show that the ground motion amplification due to basin response is controlled by the interactions of the basin geometry with faulting characteristics, including rupture initiation location and fault curvature. Compared to planar fault rupture scenarios the listric fault rupture scenarios generate higher PGV. The highest ground motion is observed in the hanging wall region and areas with deep sediments along the fault. Comparisons with Ground Motion Prediction Equations for normal faulting and ground motion maps demonstrate that part of amplification is driven by the fault curvature at depth, and it is more pronounced in the period range 1-3 s.

The Dynamics of Unlikely Slip: 3D Dynamic Rupture Modeling of Low-angle Normal Fault Rupture at the Mai'iu Fault, Papua New Guinea

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Despite decades-long debate over the mechanics of low-angle normal faults dipping less than 30 degree, many questions about their strength, stress and slip remain unresolved. Recent geologic and geophysical observations have confirmed that gently-dipping detachment faults can slip at such shallow dips and host moderate-to-large earthquakes. Here, we analyze the first 3D dynamic rupture models to assess how different stress and strength conditions affect rupture characteristics of low-angle normal fault earthquakes. We model observationally constrained spontaneous rupture under different loading conditions on the active Mai'iu fault in Papua New Guinea, which dips 16-24 degrees at the surface and accommodates ~8 mm/yr of horizontal extension. We analyze four distinct fault-local stress scenarios: 1) Andersonian extension, as inferred in the hanging wall; 2) back-rotated principal stresses inferred paleopiezometrically from the exhumed footwall; 3) favorably rotated principal stresses well-aligned for low-angle normal-sense slip; and 4) Andersonian extension derived from depth-variable static fault friction decreasing towards the surface. Our modeling suggests that subcritically stressed detachment faults can host moderate earthquakes within purely Andersonian stress fields. Near-surface rupture is impeded by free-surface stress interactions and dynamic effects of the gently-dipping geometry and frictionally stable gouges of the shallowest portion of the fault. Although favorably-inclined principal stresses have been proposed for some detachments, these conditions are not necessary for seismic slip on these faults. Our results demonstrate how integrated geophysical and geologic observations can constrain dynamic rupture model parameters to develop realistic rupture scenarios of active faults that may pose significant seismic and tsunami hazards to nearby communities. Finally, we explore the role of slip on nearby synthetic or antithetic steeply-dipping normal splay faults and how off-fault damage in the hanging wall influence shallow rupture patterns and coseismic surface displacement during large earthquakes.

Exploring Fault Segmentation and Rupture Length on the Sierra Madre Fault Zone With Dynamic Rupture Simulations

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The Sierra Madre Fault Zone (SMFZ) is a 125 km-long, north to northeast-dipping thrust fault that arcs along the southern edge of the San Gabriel and Santa Susana Mountains in Los Angeles and San Bernardino counties, southern California. Given the SMFZ's location, even a moderate earthquake on this fault would have major implications for human safety and infrastructure stability—as was the case with the 1971 M6.6 San Fernando earthquake, the most recent large event associated with this fault zone. Based on its length alone, the SMFZ is capable of producing a ~M7.7 earthquake. However, its discontinuous geometry—consisting of four primary sections, each of which are nonplanar on their own—may lead to it rupturing in multiple smaller (~M6-M7) events. Paleoseismic events at each site on the SMFZ are far enough apart to make determining a recurrence interval difficult. It is therefore also difficult to determine from observations alone whether the SMFZ typically ruptures in smaller events or whether there have ever been conditions for a multi-segment or end-to-end rupture. Dynamic rupture modeling is an ideal method for addressing questions posed by and gaps in observational data, since it calculates rupture behavior based on initial conditions, rather than requiring any a priori assumptions about rupture size. Here, we use 3D dynamic rupture simulations, incorporating complex fault geometry and observation-based initial stresses, to evaluate geometrical segmentation of the SMFZ and to determine physically-plausible rupture scenarios.

The Effects of Precursory Seismic Velocity Changes on Earthquake Sequence Simulations

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Predicting the onset and timing of fault failure is one of the ultimate goals of seismology. However, our current understanding of the earthquake preparation and nucleation process is limited. One direction towards understanding this process is looking at precursory signals preceding large earthquakes. Previous laboratory experiments have studied robust precursory signals, observed as temporal changes in pressure and shear wave velocities during the seismic cycle. The effects of such precursory velocity changes on the seismic cycle are not well understood.

We use numerical models to simulate fully-dynamic earthquake cycles in 2D strike-slip fault systems with antiplane geometry, surrounded by a narrow fault-parallel damage zone. By imposing shear wave velocity changes inside fault damage zones, we investigate the effects of these precursors on multiple stages of the seismic cycle, including nucleation, coseismic, postseismic and interseismic stages. Our modeling results show a wide spectrum of fault-slip behaviors including fast earthquakes, slow-slip events and variable creep. One primary effect of the imposed velocity precursor is the acceleration of an otherwise slow-slip event into a fully dynamic earthquake. Furthermore, the onset time of these precursors have significant effects on the nucleation phase of the earthquakes, and earlier onset of precursors causes the earthquakes to nucleate earlier with a smaller nucleation size. Our results highlight the importance of short and long-term monitoring of fault zone structures for better assessment of regional seismic hazard.

Dynamic Off-fault Failure and Tsunamigenesis at Strike-slip Restraining Bends

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We present a mechanism of tsunamigenesis for strike-slip earthquakes that involves dynamic off-fault failure at restraining bends. Dynamic rupture on a vertical strike-slip fault is modeled with undrained inelastic off-fault response incorporated by the Drucker-Prager yield criterion. We show that in a transpressive stress regime dynamic off-fault failure at restraining bends produces significantly larger surface uplift than is produced by purely elastic dislocation models. The larger uplift is due to frictional sliding with a thrust component on conjugate microfractures produced by dynamic failure, resulting in a positive flower and coseismic pop-up structure at restraining bends. In a transpressive environment where the minimum compressive stress is vertical the efficiency of producing inelastic uplift is maximum. The short-wavelength inelastic uplift, largely controlled by bend geometry, can generate localized tsunami efficiently in shallow water. Dynamic off-fault failure at fault complexities, such as restraining bends and compressional stepovers, may need be urgently incorporated in the current tsunami hazard assessments in strike-slip environments worldwide.

Multi-scale Dynamics of Complex Earthquake Faulting and Seismic Wave Propagation

Poster Session · Friday 22 April · Conveners: Kenny Ryan, Air Force Research Laboratory (0k.ryan0@gmail.com); Roby Douilly, University of California, Riverside (roby.douilly@ucr.edu); Christodoulos Kyriakopoulos, University of Memphis (ckyrkpls@memphis.edu); Eric L. Geist, U.S. Geological Survey (egeist@usgs.gov); Ruth Harris, U.S. Geological Survey (harris@usgs.gov); David D. Oglesby, University of California, Riverside (david.oglesby@ucr.edu)

Calibration of Subsurface Dynamic Parameters and Fault Geometry From Surface Fault Rupture Observations: An Example From the Shallow 2019 mw4.9 Le Teil, France, Event

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We investigate the impact of several friction, stress drop and fault geometry on surface fault rupture amount and patterns. Based on a shallow reverse surface rupturing Mw4.9 earthquake which occurred in southeastern France in November 2019, and models derived from data collected (InSAR, waveforms), we set up a rupture scenario that is consistent with the observations. From this kinematic scenario we constrain the dynamic parameters of the deeper part of the rupture (300-2 km depth), while we test the shallow part parameters (<300m). The surface rupture produced by the different models are then compared to the surface deformation patterns and amplitude.

We show that the shallow surface layers are likely slip-strengthening, but also that the surface rupture is not a passive marker of the deeper rupture process: they are both linked. The frictional behavior (Dc, Stress drop, weakening or strengthening) directly modulates the amount of surface rupture.

Dynamic rupture history notably differs from the kinematic model, although the friction evolution of the first was directly derived from the second. Adding a secondary structure in the northern part improves significantly the surface rupture fit, as well as the rupture history. Finally, such a shallow reverse fault earthquake seen through its dynamics emphasizes a puzzling question: what is the absolute level of stress on a seismogenic fault so close to the surface?

High-frequency Ground-shaking Variability From Rough-fault Ruptures

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Geological observations reveal that fault-surface topography has variations at large scale (segmentation) and at small scale (roughness). These fault geometrical complexities influence earthquake rupture dynamics, seismic energy radiation and resulting ground-motion and its variability. Earlier studies have investigated the role of fault-segmentation in governing rupture dynamics and ground-motion, but the understanding of fault-roughness effects on ground-shaking and its variability is still limited. In the present study, we investigate fault-roughness effects on ground-motion variability as a function of distance using 3D dynamic rupture simulations. We consider different fault-roughness parametrizations (realizations and heights of roughness) and nucleation positions (unilateral and bilateral ruptures). We use a generalized finite-difference method (Ely et al., 2008) to compute synthetic waveforms (max. resolved frequency 5.75 Hz) at numerous surface sites nto carry out statistical analysis.

Our simulations reveal that ground-motion variability from unilateral ruptures remains nearly constant with increasing distance from the fault, and is comparable or higher than estimates from ground-motion prediction equations (e.g., Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008). Ground-motion variability from bilateral ruptures decreases with increasing distance from the fault, which contrasts with earlier studies (e.g., Imtiaz et. al., 2015) that observe increasing variability with distance. Ground-shaking variability from unilateral ruptures is higher than from bilateral ruptures due to hypocenter location (rupture directivity) and complex seismic radiation patterns related to fault roughness. Moreover, ground-shaking variability for rougher faults is lower than for smoother faults. In summary, our results help develop a fundamental understanding of ground-motion variability at high frequencies (~ 6 Hz) due small-scale variations in fault-surface topography.

Investigating the Effects of Fault Dip Angle on Rupture Propagation Along Branch Fault Systems using 3D Dynamic Rupture Simulations

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An important consideration in assessing seismic hazards is determining what is likely to happen when an earthquake rupture encounters a geometric complexity such as a branch fault. Previous studies show parameters such as branch angle, stress-orientation and stress heterogeneity as key factors in the self-determined rupture path on branch faults. However, these studies were conducted in 2D or in 3D with vertical faults. Many natural faults have some dipping component. In this study, we investigate the effects of dipping angle on rupture propagation along branch faults using the FaultMod 3D dynamic rupture code. Preliminary results suggest that under certain conditions shallower dip angles can facilitate through going rupture.

Peculiar Rupture Path of the 2019 Peru Intraslab Earthquake Suggests a Key Role of the Surface-reflected Dynamic Stresses

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The 2019/05/26 North Peru earthquake (M_w=8) is a major intermediate-depth earthquake that occurred close to the eastern extremity of the Nazca slab flat part. We carried out a joint analysis of its rupture process using high-frequency back-projection and seismo-geodetic broadband inversion. The latter approach shows that the earthquake propagated with almost purely normal faulting on the 60° eastward dipping plane, and both imaging techniques provide a very consistent image of the peculiar space-time process of the earthquake: its 60-second long rupture is characterized both by a main Northward propagation (resulting in a rupture extent of almost 200km in this direction) and by a reactivation phase of the hypocentral area, particularly active 35s to 50s after origin time. Given the depth of this earthquake (125-140km), this reactivation time window coincides with the arrival time of the surface-reflected dynamic wavefield. Computed values of the dynamic Coulomb stresses associated with this wavefield are of the order of ten to several tens of kPa. According to previous studies, dynamic triggering was observed at such stress levels, and the reactivation phase of the Peru earthquake may thus originate from fault locations that were brought close to rupture by the initial front before being triggered by the reflected wavefield. Source time functions of other large intermediate-depth earthquakes further suggest that such a mechanism is not an isolated case.

Revisiting the 1906 M 7.1 Meishan, Taiwan, Earthquake: A Dynamic Rupture Modeling Perspective on Single-fault Versus Multi-fault

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The March 17, 1906 (UTC) M 7.1 Meishan earthquake is one of the most devastating events in Taiwan's history. The investigation in the past 100 years on this large event is rather limited due to the lack of seismic observation. However, with the advent of numerical simulations, dynamic rupture modeling provides an additional technique to understand source properties and the rupture process of the Meishan earthquake. In this study, the primary target is to revisit the source and assess the dynamic parameters for the 1906 Meishan earthquake. Based on physical and mathematical constraints from frictional limit, fault geometries, fluid pressure, rock strength, empirical flow law, static friction coefficient and stress drop, we build up 192 models for the experiment. By comparison of the resulting rupture conditions from the suite of ruptured models, we discuss the possible ranges of dynamic parameters for the historical earthquake. Following the selection of the most reasonable models, we compare the polarities and amplitudes of the synthetic waveforms to the waveforms observed on Omori seismographs in addition to the intensity maps in conjunction with the distribution of the aftershocks of the 1906 Meishan earthquake.

According to the rupture process, waveform comparison and seismic intensity simulation, the results provide considerably well-fit polarities and amplitudes from waveforms and similar intensity patterns with historical intensity maps for multiple-segment models. This study indicates that rupture occurred on multiple faults connected to the Meishan fault rather than on the Meishan fault alone. The results in this study suggest that the Meishan earthquake with its thrust fault association is closer in its faulting characteristics to other major events in western Taiwan, such as the 1999 Chi-Chi earthquake, due to this not yet widely considered thrust component.

The Ingredients Needed for Realistic Dynamic Earthquake Rupture Simulations

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Many mysteries about earthquake mechanics remain unsolved, including significant questions about what causes large earthquakes to stop after they have started propagating and which physical processes of the earthquake source are most likely to affect strong ground shaking. The SCEC-USGS dynamic earthquake rupture group aims to solve these mysteries, using computational simulations of spontaneous earthquake rupture propagation in conjunction with available field and laboratory data. Our group has met four times in workshops over the past three years to discuss 'ingredients' (assumptions) needed for developing comprehensive computational simulations: fault geometry, fault friction, rock properties and stress conditions. We need to figure out which choices to make for each of these ingredients, among the myriad of possibilities, and we also need to figure out which of the ingredients can be simplified, due to either lack of knowledge of their true nature or lack of sufficient computational power to include all of the fine details. At our ingredient-focused workshops, we have learned about SCEC community models useful for our endeavors as well as new research often applied to specific earthquake settings. We have also debated the relative significance of each ingredient. Key lessons we have learned during our discussions have been that all four of the

ingredients (fault geometry, fault friction, rock properties and stress conditions) are important, and that sometimes these should be implemented in not just two-dimensions, but in the full three-dimensional space that is Earth's seismogenic zone. The overall lesson is that earthquake mechanics is still a nascent topic, and new field observations, lab experiments and computational simulations will help provide more solutions to how earthquakes work.

Network Seismology: Recent Developments, Challenges and Lessons Learned

Oral Session · Friday 22 April · 2:00 PM Pacific

Conveners: William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Kris L. Pankow, University of Utah (pankowseis2@gmail.com); Renate Hartog, University of Washington (jrhartog@uw.edu)

Earthquake Detection in Northern California With Graph Neural Networks

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We present a Graph Neural Network (GNN) architecture for earthquake phase association, in which we process pick datasets, determine the number and location of earthquakes and associate picks to each source. We design this network to be effective in realistic regional monitoring scenarios (100+ km aperture networks), where station geometry can be time varying, heterogenous, and with numerous earthquakes occurring closely in space and time. We use a combination of internal graphs: one representing station configuration and the other representing a sparse set of candidate nodes that spans the source region. The GNN solves the association problem by applying graph convolutions to the pick data on these graphs and mapping to continuous space-time prediction targets of source hypocenter and source-arrival association likelihoods. It makes use of station heterogeneity, giving the model a strong inductive bias to focus on contextual insights observed on subsets of neighboring stations, while making inferences.

The model was trained on synthetic data, and the input pick streams include variable station geometry, event rates, false pick and miss rates, etc. It was tested on real data from the NC network of northern California, using PhaseNet-produced picks as input. We recover at least 95% of previously reported USGS earthquakes > M1 throughout the interval 2000 – 2020. The spatial residuals of matched events between our locations and the USGS catalog have means of near zero and ~0.08° standard deviation. The source locations predicted by the GNN and the locations obtained by standard travel time location of the associated picks predicted by the GNN are consistent. Double-difference earthquake locations of the picks associated by the GNN further improve source resolution of faults in northern CA, such as the SAF, Hayward and Calaveras faults, improving confidence in the associators ability to accurately resolve the problem. Initial applications also suggest a substantial number of new events < M1 are detectable, and work is ongoing to build a new catalog for northern CA and quality control the new detections.

Toward Integrating Machine Learning Phase Pickers Into the Southern California Seismic Network Earthquake Catalog

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Southern California Seismic Network (SCSN) seeks to incorporate automatic phase picks from the Generalized Phase Detection (GPD) machine learning model (Ross et al., 2018) to its operational earthquake processing. GPD, trained on millions of manually-picked P- and S- arrival times from Southern California earthquakes, has potential for reducing analyst workload and accelerating availability of a more complete earthquake catalog, especially during active earthquake sequences.

We assess how accurately GPD can pick P and S phases for known earthquakes already identified by the ANSS Quake Monitoring System (AQMS) software, which is routinely used to create the authoritative SCSN earthquake catalog. We applied GPD to triggered event waveforms archived by the Southern California Earthquake Data Center, at 0-100 km epicentral distances, for ~25,000 earthquakes from 2020 and all magnitude 4+ earthquakes in 1984-2021. For comparison, we compute residual time differences between ground-truth analyst picks and GPD picks at each channel and station. These residuals are small, with a mean below -0.05 seconds (overall slightly later than analyst picks), and a standard deviation below 0.2 seconds. We also compute recall, which tells us the proportion of analyst picks successfully identified by GPD. Recall values are 90-95% for all events in 2020, but drop to 70-80% for all magnitude 4+ events, indicating that GPD is not as good at picking analyst-identified phases for larger earthquakes. We describe progress and challenges associated with two parallel efforts to integrate GPD into AQMS, and evaluate their effects on the SCSN earthquake catalog: 1) Refining locations for magnitude <2.8 events detected by AQMS by incorporating GPD picks in post processing, 2) Having GPD directly detect phases on real-time continuous seismic data, to determine how well GPD detects new events that were missed by AQMS.

On-premises Integration of Machine Learning Models at UUSS—Distributed Computing and Messaging

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In less than a decade machine learning (ML) has revolutionized seismology. Of interest to regional seismic networks are ML successes in signal detection, characterization of arrivals, source discrimination and association. As University of Utah Seismograph Stations (UUSS) looks to implement these new models into an operational setting we are challenged by (1) the number of new models constantly being produced, (2) the fact that models can be trained in a variety of ML frameworks - e.g., TensorFlow, PyTorch, SkLearn and (3) that the requisite computational time to perform a model evaluation is substantially more than our existing baseline models. The natural solution is to containerize each model and, for the more computationally intensive models like detectors, place the container on specialized, dedicated hardware. Unfortunately, our current seismic system is difficult to use in this desired distributed computing framework. To mitigate this shortcoming, we present a new, lightweight, secure and high-performance messaging framework built on ZeroMQ; UUSS Message Passing System (UMPS). UMPS uses a hub-and-spoke architecture to overcome the network discovery problem and can quickly connect disparate data broadcasts, services and ML-enabled modules (spokes) through a stable enterprise-bus (hub). This allows different physical and logical segments of a processing pipeline to utilize publish/subscribe and request/reply messaging patterns across a network without any individual module knowing the network topology a priori. We anticipate that UMPS, when paired with containers, will allow UUSS to quickly evaluate and integrate new ML models into operations as they become available.

Event-based Training in Label-limited Regimes

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Specific attributes of a seismic source are typically assigned at the terminal end of seismic event processing where observations pertaining to a specific seismic source are merged to create stable and accurate estimates of source properties such as event magnitude and source type. In station-centric information processing, such as making detections, determining phase ratios, or measuring the length of coda wave decay, we typically process incoming data streams independently, even though we are in part measuring properties of a seismogenic source that are shared across observations. This work develops an approach for information sharing across non-independent observations through a domain-informed regularization term applied during gradient-based learning. I apply the event-based regularization to a simple feed-forward neural network with simulated data to discuss how dataset structure interacts with the assumptions inherent to regularization approaches for semi-supervised learning. I then demonstrate the effectiveness of event-based training using a deep convolutional neural network for seismic event classification.

Nodal Deployments and Their Role in Regional Seismic Monitoring

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The last decade has seen the emergence of seismic nodes that are small packages that include (a) geophone(s) and a battery, nominally designed for active-source acquisition, that are able to continuously record data for several weeks at time. Increasingly, researchers have leveraged these datasets to record the full seismic wavefield and at a station density much greater than can be achieved with broadbands because of their lightweight packaging and ease of deploying hundreds in a matter of days. We report on our efforts to utilize nodes to infer region-specific characteristics across the state of Oklahoma and envision a future for their automatic inclusion into regional seismic networks (RSNs). OGS developed and continues to update a Python package, easyQuake (https://github.com/jakewalter/easyQuake), that consists of a flexible set of tools for detecting and locating earthquakes from FDSN-collected or field-collected seismograms. The package leverages machine-learning phase pickers, coupled with an associator, to produce a Quake Markup Language (QuakeML) style catalog complete with magnitudes and P-wave polarity determinations. The program outputs catalog QuakeML-formatted files that can be split into individual event QuakeML files. We have added submodules that detect, locate and re-locate events from node arrays and will present a few case studies from Oklahoma deployments. We show that while many of the research datasets are not appropriate for direct inclusion into ANSS data products, the results of those studies can directly inform how the RSN conducts science in subareas of the state and it can serve a broader public information role. As several midcontinent states strategize about storing CO_2 deep underground to realize net-zero greenhouse gas emissions goals, small arrays within larger seismometer backbones may be a solution for seismicity risk management under regional carbon storage programs. Developing reliable autonomous tools for earthquake identification on portable and easily deployable sensors would be one key step forward in de-risking carbon storage.

Learning Lessons and Sharing Solutions With ANSS NetOps Workshops

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The Advanced National Seismic System (ANSS) conducts periodic workshops for seismic monitoring technical staff called NetOps Workshops. The first NetOps was hosted by the University of Utah Seismograph Stations (UUSS) in February 2006, with 42 participants from 22 organizations (at which the idea for an ANSS Depot was born). The eleventh NetOps in November 2021 was all virtual with over 240 participants from 39 organizations. During the workshops, technical staff across the ANSS and partner organizations give presentations and exchange ideas and best practices. Scattered staff can consider ways to work more closely to promote the operation of the ANSS as an integrated system. Each workshop culminates in a "messages for management" session where participants contribute recommendations from technical staff to management. While the resources do not exist to act on all recommendations, some notable findings include:

Many networks are independently solving the same engineering problems. Collaboration among technical staff, especially in power systems and RF telemetry can be very useful.

Network reliability is being improved with dynamic routing methods, but reliability and wide adoption requires investments in staff and equipment.

Cloud applications for data acquisition and processing are maturing.

Network design for regional seismology may face challenges with the early warning mission. Monitoring prioritizes data completeness, while EEW can only use low latency data. Dataloggers, algorithms and telemetry design all need review.

Management should watch for ways to expand roles and connectedness of analysis and operations staff.

Common repositories for standard tools, metrics and best practices for both technical and safety procedures reduce duplication of effort.

Better integration of Education and Outreach efforts across monitoring systems is needed.

Data Mining a Large Station Metrics Database to Guide Station Siting

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The Pacific Northwest Seismic Network (PNSN) is responsible for monitoring seismic activity in WA and OR and is also part of the USGS ShakeAlert earthquake early warning system. Fulfilling our role effectively requires monitoring metrics related to state of health, telemetry, waveform quality, site noise and those specific to ShakeAlert. We store, view and mine these metrics using SQUAC, the Seismic Quality Assessment Console https://github.com/pnsn/squac/wiki. SQUAC consists of a backend database with an API for interfacing, a user-friendly python client to simplify reading and writing and a web-based GUI with dashboards and alarms. We currently collect or calculate about fifty metrics internally from thousands of channels from ANSS regional seismic networks. External partners are also contributing to the database. Most metrics are calculated every ten minutes, hourly or daily with little lag from real-time. Millions of measurements are added each day to the database which currently has about two billion rows. A recent use case that we highlight here is data mining various noise metrics from hundreds of three-channel strong motion (SMA) sites and comparing with distances to known sources of noise such as roads, occupied buildings, dams and rivers to help guide siting new stations as we help build out ShakeAlert. We find that in areas where cultural noise cannot be avoided and only a SMA sensor would be appropriate, that at least 50 meters to the nearest road with daily car traffic is best. At closer distances, the amplitudes of signals from passing cars and background noise levels approach values making detection of local small (~M2) earthquakes difficult. Our recommendation is grounded in comparing metrics from hundreds of stations, many at schools and fire houses at various hours of the week before and during the pandemic when schools and businesses were mostly closed. We also find that the signal from passing cars traveling more than 20 mph is almost always more important to consider than proximity to other cultural noise sources like buildings, sidewalks, rivers or tall towers that rattle with wind.

An Overview of Quality Assurance Efforts at the Alaska Earthquake Center

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Quality Assurance (QA) efforts at the Alaska Earthquake Center focus on developing and maintaining routine QA procedures for network operations within the state of Alaska. Our QA procedures include monitoring: seismic stations for state of health, integrity and quality; meteorological and infrasound data streams adopted from the USArray program; as well as the real-time and analyst-review catalogs of Alaska seismicity. Through the use of in-house metrics and procedures, coupled with externally created software, the Center's QA team is able to ensure that downstream users have access to high-quality data and the best earthquake catalog available for the state of Alaska.{p dir="ltr"}Products created by the Center's QA team include bi-weekly reports that focus on seismic data integrity and quality issues. Metrics used in the bi-weekly reports include those computed in-house and those available through IRIS's MUSTANG system and QuARG (Quality Assurance Report Generator, a software created at IRIS for flagging issues and generating reports). Additionally, monthly reports with information regarding the health and integrity of our meteorological and infrasound sensors are produced and submitted to external stakeholders, and a monthly report on the real-time (automated) system performance is archived in house. Quarterly technical reports are all-encompassing, and in addition to the data from bi-weekly seismic and monthly meteorological/infrasound reports, include daily data return rates and data gaps for the Alaska network, average monthly completeness, stations with data quality and integrity issues, first solution latencies, alarm and duty latencies. These quarterly technical reports are published as public-facing citable white papers.

Posthole N4: Potential Improvements in Data Quality and Station Reliability From Posthole Versus Vault Installations

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In 2019, the USGS Albuquerque Seismological Laboratory (ASL) adopted >140 stations from the Central and Eastern United States Network (CEUSN; N4 network code). These stations were first installed as part of the EarthScope Transportable Array (TA). About 1 in 4 TA stations (hence the N4) were chosen to continue operating past the TA's standard two-year lifespan. Transitioning the N4 from a portable to a permanent network has proven challenging due to aging station infrastructure. The design of the TA-style vaults satisfied (and often surpassed) the operational needs of the initial deployment. However, 10-15 years after installation, many vaults have begun to leak, exposing equipment to highly unfavorable operating conditions.

As we tackle the maintenance backlog accumulated during the 2020-2021 COVID-19 pandemic, we seek to implement new practices that will ensure high data quality and reliability. One advance, facilitated by novel sensor design and emplacement techniques, are "posthole" installations. Postholes bridge the gap between a typical vault or pier-type installation and a deep borehole. They allow networks to cost-efficiently increase reliability of equipment and reduce noise, particularly at frequencies >1 Hz, or on horizontal components of broadband sensors at periods >20 s. In 2021, ASL field engineers used an auger rig to install postholes at two N4 stations and two Oklahoma aftershock stations. The grouted, PVC-cased postholes reach depths of 2-10 m in soft sediments. We present initial results from the 4 upgraded sites, including a cost estimate and installation schedule, a comparison of noise before and after the upgrade and implications for regional network monitoring. Broadly, the new postholes provide long-period horizontal data of equal or superior quality to the previous installations, with deeper emplacements reaching a lower long-period horizontal noise floor. Evaluating reliability will require a few more years of observation.

Raspberry Shake Citizen Seismological Network

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The Raspberry Shake seismological network is the largest real-time streaming earthquake monitoring network in the world. The network has more than 1400 stations online, streaming and generating origins in real time, all handled by the SeisComP software suite. As stations are being installed by non-seismologist experts all around the globe data quality control is paramount. Everyday new stations are being installed, increasing the data streaming load and resources required for timely data processing. As the network density rises, the location gap and the minimum detection magnitude thresholds are reduced, improving the detection capabilities and reducing dissemination time. Here we present the challenges faced since the Raspberry Shake AM network was born in late 2016, how these issues have been resolved and the future of the network.

Network Seismology: Recent Developments, Challenges and Lessons Learned

Poster Session · Friday 22 April · Conveners: William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Kris L. Pankow, University of Utah (pankowseis2@gmail.com); Renate Hartog, University of Washington (jrhartog@uw.edu)

Aftershock Relocations Using Nonlinear Inversion, 1D and 3D Velocity Models and Machine Learning to Image Fault Structure

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On March 18, 2020, a magnitude 5.7 earthquake hit the Salt Lake Valley in the state of Utah. This mainshock triggered approximately 2600 locatable aftershocks over the following 18 months, a small but significant number of which were felt by the local population. Using a dense geophone deployment and machine learning, an additional several thousand events were detected and located. Currently, both the mainshock and the majority of the aftershocks are suspected to have occurred on or near a deeper portion of the Wasatch Fault, a large range-bounding fault system thought to be capable of generating a M_w 7.5 earthquake. However, a small subset of aftershocks may have occurred on a portion of the more steeply, eastern dipping and poorly understood West Valley Fault system, which is likely subsidiary to the Wasatch Fault. Unfortunately, the catalog locations and limited number of resulting focal mechanisms for this subset of aftershocks provides only a crude constraint on the true fault structure. To better illuminate the fault structure, we use a nonlinear location method and both 1D and 3D regional velocity models to relocate the catalog of events. Preliminary results indicate that the events located near the West Valley Fault Zone may be located in a very heterogeneous seismic velocity area—as both 1D and 3D models show significant spatial scattering of this event cluster. We hope to further refine the locations using static station corrections and use machine learning models to reduce the calculation time and storage requirements for utilizing 3D models.

Arizona's Seismic Network: A Case Study in Balancing Growth, Risk and Resources

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As the southwest grows more populous the need for seismic monitoring becomes more relevant. The state of Arizona's population has nearly doubled from 3.7 million in 1990 to 7.3 million in 2020 (United States Census Bureau). The population growth and increased urbanization has resulted in a greater need to protect critical infrastructure such as the Palo Verde Nuclear Generating Station, the largest of its kind in North America. Although Arizona's seismicity rate is considered low, moderate events do occur about every decade. Additionally, the potential for larger events exists in areas with active faulting such as the southeastern and southwestern parts of the state and the Northern Arizona Seismic Belt which includes the Grand Canyon and greater Flagstaff area. The largest historical earthquake of the southern Basin and Range, the M 7.6 Pitaycachi Earthquake of 1887 occurred less than 60km from the town of Douglas, AZ (Suter, 2014; DuBois and Smith, 1980). The Pitaycachi fault has a slip rate of approximately 0.06 to 0.08mm/yr, resembling estimated slip rates for many faults in the southern part of Arizona. Historical moderate earthquakes include 3 > M6.0 near Flagstaff in 1906, 1910 and 1912, as well as the M 5.3 Cataract Creek sequence of 1993, the Holbrook M5.2 in 2005 and the Duncan M 5.2 in 2014. In 1977, Northern Arizona University began establishing a permanent short-period seismic network in northern Arizona that grew to seven stations. In 2008, the Arizona Geological Survey (AZGS) adopted 8 legacy Transportable Array (TA) stations to cover the central and southern half of the state. In 2017, AZGS added six stations to improve coverage of parts of northern Arizona. In 2018, the AZGS adopted the remaining two TA reference stations, bringing the total broadband stations to fifteen. The increased station spatial coverage over the last decade has improved the detection threshold to about M 3.0 for most of the state.

Caravel: A New Seismic Monitoring System

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The Istituto Nazionale di Geofisica e Vulcanologia (INGV) is the operational center in charge for monitoring Italian earthquakes. The surveillance system is designed to provide information to the Department of Civil Protection (Dipartimento di Protezione Civile [DPC]) and to the public. Such systems and related services are funded by the Italian Government (Presidenza del Consiglio dei Ministri) based on a formal agreement between INGV and DPC.

Technological improvements in the last years were taken into account for devel- oping new protocols and software to upgrade all the procedures actually in use in the monitoring centers. A new software architecture, based on a new database schema capable of representing all information coded in the QuakeML format, and a set of OpenAPI specifications have been redesigned and developed in order to standardize the interaction of software that produce and review scientific products.

Real-time earthquake evaluation consists of phase picks, preliminary and automatic hypocenters, local magnitudes and ground-motion parameters. The real-time analysis system presently in use at INGV was the starting point for Caravel, the new multitier compound system that relies on four main components: an automatic earthquake detection and location systems based on multiple instances of Earthworm; a new seismological relational database for parametric data called QuakeDB; a full set of new web services application programming interface specifications to share information and provide data at the application level called Dante and, finally, a multiplatform interactive revision tool developed to analyze, use and review the seismic parameters in real-time called PickFX. Such a system has been engineered to access the EIDA data and interact with the International FDSN (Federation of Digital Seismic Networks) standard web services. INGV personnel are now testing the Caravel system for being ready in the next future to use it in the Italian Seismic Surveillance system.

Denoising Seismic Waveforms Using the Continuous Wavelet Transform

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Removing noise from seismic data to increase signal-to-noise ratios is one of the most important problems in seismology. An abundance of preprocessing methods have been applied to extract signals out of noisy data. One well-explored approach is the band-pass filtering of seismic waveforms in the frequency domain. But this approach does not always isolate signal from noise, as problems arise in cases where signal and noise frequencies overlap. More efficient methods include thresholding the signal in the time-frequency domain, which has been shown to be more effective in suppressing noise. However, based on the implementation of different signal transforms, this method can pose problems if one wants to accurately identify spectral peaks due to a trade-off with time resolution. More recently, Langston and Mousavi (2019) used the continuous wavelet transform (CWT; Grossmann et al., 1989; Starck et al., 2010) to represent time-series data in a more compact form and found that using the CWT allows for efficient decomposition of the signal, into a superposition of nonstationary components of time-scale members and individual constitutive phases (Herrera et al., 2014).

Increased noise in the microseismic band is a challenge to lowering regional monitoring thresholds. The application of a filtering method that removes microseismic noise, thus isolating the seismic signal, will be key to better utilization of improved short-period waveform simulations. To this effort, following the Langston and Mousavi (2019) CWT application we developed a Python-based toolset that implements the CWT-based non-linear thresholding operations to de-noise or de-signal seismic data. We test this application using the 2020 Mw 6.5 Monte Cristo Range earthquake sequence to assess automation and portability into a processing scheme. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-830511.

Determining Seismic Station Timing Accuracy Using Regional Stations

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Modern seismic digitizers use the Global Navigation Satellite System (GNSS) to provide extremely high precision timing (down to 1–2 μs). However, there are cases where a reliable GNSS signal lock cannot be obtained resulting in unknown timing accuracy. These cases can include physical damage to the antenna or GNSS engine board, or digitizer firmware or software that doesn't accurately account for leap seconds or binary "roll over" dates in the GNSS signal. The accuracy and precision of timing across a seismic network are critical for determining correct phase arrival times used in locating earthquakes and in tomographic studies. Previous studies have used recordings of repeating earthquakes or blasts, cross-correlation of microseisms over time or comparison with synthetics to estimate apparent changes in relative timing quality of seismic stations as a function of time.

In this study, we examine possible timing errors at seismic stations using predicted seismic phase arrival times of teleseismic earthquakes across a regional network. We select seismic data for a time window around the first arriving seismic phase at each station and cross correlate it with the seismic station being studied to determine the measured relative delay versus the predicted relative delay between stations. Differences in local velocity structure can cause small arrival time differences; however, systematic changes in relative timing delays at an individual station between successive earthquakes likely indicate timing errors. We show examples of stations that have lost GNSS lock and the timing has remained relatively good; examples of timing errors that have slowly drifted and gotten worse over several months; and examples of abrupt jumps in timing errors of up to 5-6 seconds. Using this technique, we can identify timing errors on the order of +/- 0.5 seconds without needing to install a reference sensor nearby to verify timing.

Digital Radio Telemetry Issues in Network Seismology

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Network seismology increasingly relies on equipment that provides a digital (serial or ethernet) data stream from the station. The University of Utah Seismograph Stations (UUSS) operates more than 250 seismic stations and telemetry aggregation sites in the Utah and Yellowstone regions. Of those, more than a third rely on radio links to bridge ethernet and serial networks. Over many years, we've encountered a variety of issues that degrade or disable radio links that would otherwise appear to be of good design. Here we report on problems for radios attached to busy ethernet networks, use of higher-than-necessary radio power and antenna separation, and the dangers of using factory default settings when deploying radios. We focus primarily on radios from Freewave and Intuicom since these make up the highest use in our network, but the issues can apply equally to similar radios. We detail some of these problems, how they were diagnosed and the fixes we have implemented.

Earthworm and AQMS for Earthquake Data Acquisition and Management in the Cloud at the California Strong Motion Instrumentation Program

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Earthquake Management Systems (EMS) have traditionally been located on-premises at Regional Seismic Networks (RSN) since that is where the majority of data acquisition has been performed. As RSN's begin using more advanced digitizers that are connected to the internet via non-dedicated pathways (e.g., cellular modems and other public internet interconnects), having all of the data flow through a central on-premises network is no longer necessary. A recent development by ISTI for the California Geological Survey has been to dockerize the AQMS EMS to provide all of the functionality necessary to acquire seismic data and locate earthquakes in a cloud environment. While the example at CGS is using an Azure environment, because the development was using Docker containers, the services provided can be installed in any managed cloud environment.

Data sources are imported and processed through Earthworm modules as normal, but all of the Earthworm modules run in a single docker container. In separate containers, the data is archived to Winston Wave Server and MariaDB, and it is made available via FDSNWS portable dataselect. AQMS functionality is broken out to separate programs in individual containers. External events can be incorporated into the AQMS database via PDL. While the test base only used a dozen stations, it is expected that over 200 strong-motion stations in California will be available soon.

Cloud managed systems through docker provide a number of benefits to RSN's. Primarily is that there is a complete off-site backup system that could be located outside any areas that could potentially have earthquake damage. Likewise, dockerized systems are easier to create and manage to allow for easy expansion of networks. In addition to being easier to manage and providing offsite capabilities, dockerized software systems are often more robust because they can be monitored and restarted easily if one component should fail.

Ensuring Timing From Nodal and Network Seismic Systems Is Synchronized

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The ability to combine nodal deployments with continuously operated network stations can provide significant resolution enhancement for local seismicity. In order to ensure accurate timing and locations, we use data collected during a seismic survey to compare times at permanent stations. The Source Physics Experiment (SPE) conducted a seismic survey in Rock Valley, NV during the spring of 2021. The survey was deployed along roads, with 188 three-component receivers at 100-m offset and 553 source locations at 25-m offset. Data from five accelerated-weight-drop hits were collected with the source in the vertical position, and five at 45 degrees to vertical, perpendicular to the source line in both directions, for a total of fifteen hits at each source point. Two permanent stations, RTPP and RVEE, also recorded signals from the sources within 0.5 km of the station. The permanent stations have both a surface and a borehole instrument (~90 m below the surface). As expected, when the source distance decreased, we observed a dramatic increase in correlation. A ring of hits was also conducted around each station. These provided a mechanism to verify the orientations of the sensors and verify each borehole instrument's position with respect to the well casing. In addition, we look at velocity anomalies associated with the direct arrivals and compare to the velocity models generated by other studies.

Evaluation of MEMS Sensor Reliability Through Comparative Analysis of Seismic Records and Field Experiment Using 2021 Jeju Earthquake

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MEMS (Micro Electro Mechanical Systems) sensors can record 3-components accelerations and are easy to attach to wireless network communication system to transmit data in live. This feature makes the MEMS sensor popular to be used as auxiliary seismic observation networks worldwide. In South Korea, more than 6,700 MEMS sensors have been distributed and installed in the structures. However, due to the installation location, these sensors measure the ground motion as well as structure responses, and they also have relatively high noise floor. Thus, to use MEMS sensor records equivalent to records from seismic stations (SS), signal post-processing is an essential work. To analyze reliability of MEMS sensor records, we compared the seismic motions recorded at SS of Korea Meteorological Administration (KMA) with motions recorded by MEMS sensors for the M4.9 earthquake occurred in Jeju on December 14, 2021. The natural logarithm residual of the SS PGA and the residual of the MEMS peak horizontal acceleration (PHA) were obtained using a South Korea specific ground motion model (GMM). We calculated the event term as the average residual of SS records and removed the event term from SS and MEMS sensor residuals to ignore the event bias on the residual. Field experiments were also conducted to evaluate the reliability of MEMS sensors and to confirm the response of each structure. A total of 15 locations including KMA seismic stations and buildings where MEMS sensors installed in Jeju were target. We recorded the ambient noise about 30 minutes at points on the ground surface nearby the building, MEMS sensor installation location and the roof of the building. The ratio of ambient noise at each pair of measurement points provided the building and MEMS sensor responses, which used to evaluate the reliability of MEMS sensor record.

Idaho National Laboratory Seismic Monitoring Program

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The Idaho National Laboratory (INL) Seismic Monitoring Program began as a single station in 1971. The network has grown to include 37 seismic stations, 20 strong-motion accelerometers (SMAs) and 17 Global Positioning Stations (GPS). INL resides on the Eastern Snake River Plain (ESRP), located in southeast Idaho. INL has a history operating nuclear test reactors and is currently designated as the Reactor Innovation Center. During the last five decades, the INL seismic network has undergone several periods of major upgrades to support evolving nuclear-related missions at INL. The first network upgrade included installation of several short period analog seismic stations and accelerometers before and in response to the 1983 moment magnitude 6.9 Borah Peak, Idaho earthquake. By 1987 10 seismic stations and 19 SMAs were in operation both within and around the INL site boundaries. The second upgrade included conversion from paper to digital seismograms using a CUSP (Caltech-USGS Seismic Processing) system in the early 1990's along with installation of 19 more seismic stations. This was followed by a transition from CUSP to EARTHWORM and replacement of analog station instrumentation to digital field dataloggers in the early 2000's. The next major upgrade, between 2003 to 2009, was the installation of 15 permanent GPS receivers in and around the ESRP supplemented with several campaign GPS surveys. The final upgrade from 2010 to 2019 included installation of several new seismic stations, acquisition of a Transportable Array station, upgrades from short-period to broadband seismometers and replacement to newer accelerometers. Along with upgrades to seismic instrumentation, network telemetry instrumentation also advanced. Each of these periods of growth improved detection sensitivity and waveform recording to allow better characterization of seismicity and tectonics in and around the ESRP. This presentation will discuss the evolution of the INL seismic network in further detail and will also discuss the challenges encountered and what was done to overcome them.

Improving the Reliability of the Alaska Earthquake Center's Field Monitoring Networks

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The Alaska Earthquake Center (AEC) maintains approximately 250 seismic and environmental monitoring stations throughout the state of Alaska. The environs of AEC stations range from isolated, remote wilderness locations only accessible by helicopter during the limited Alaska summer to industrial yards and public building utility rooms. The diverse settings of AEC monitoring stations requires equally diverse telecommunication strategies to maintain real-time earthquake monitoring across the state. These strategies include satellite communications using Hughes Gen2 and BGAN systems, cell modems on cell networks ranging from 2G to 4G, 900 MHz radio links, tapping into the Alaska state microwave network (SATS) and piggybacking on public and private internet connections in remote villages and wilderness lodges. Site power systems are equally diverse ranging from a variety of stand-alone solar power based systems designed to survive through the long, dark and snowy Alaska winter to simply plugging equipment into the nearest wall outlet.

This presentation details the on-going efforts by past and current AEC field staff to improve site and network reliability through constant improvements to the field site power and network communications systems. Recent developments include attempts to improve and harden the power systems at critical communication hub sites, evaluating the feasibility of secondary gateways to field networks, capitalizing on the expanding cell coverage in Alaska and improving network and systems redundancy with routing and virtual machine instances on Amazon Web Services. We will also discuss the challenges of maintaining and improving network performance of sites located remote locations and operating under harsh environmental conditions.

ISC Datasets for Seismology

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The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale based on the collaboration with ~150 seismic networks around the world. We describe recent achievements in rebuilding the entire ISC Bulletin using the new ISC locator, ak135 velocity model, more robust magnitudes and inclusion of the first motion based source mechanisms. We note the recent ISC

efforts in constraining the depths of moderate to large seismic events by taking the depth phase arrival time measurements from the waveforms freely available on-line and building Probabilistic Point Source Model solutions.

In addition, we produce several specially designed data products that stemmed from the ISC Bulletin and allowed ISC to assist several different areas of seismological research. These datasets include ISC-EHB dataset (1964-2017), ISC-GEM catalogue (1904-2018), IASPEI Reference Event List (GT), ISC Event Bibliography (1904-2021). We also describe the supplementary datasets: the Electronic Archive of Printed Station/Network bulletins, the ISC Dataset Repository and the International Seismological Contacts.

Mission-critical Real Time Data Acquisition: An Earthquake Early Warning Case Study

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Ensuring the reliable acquisition of real time seismic data from remote monitoring stations is an inherently challenging task. Stations are often in isolated locations with little to no supporting infrastructure, creating limitations on power and communications systems which demand design tradeoffs. When the data is driving mission-critical public safety systems, such as Earthquake Early Warning (EEW) networks, real time acquisition performance is of critical importance.

In particular for EEW, acquisition performance must be measured not only in real time data availability, but also data latency and bandwidth utilization. Beyond these key performance metrics, it is critical that the system is robust, with layers of redundancy to ensure continued operation in the event of a damaging earthquake. A comprehensive system test and acceptance program is needed to ensure performance requirements are met and to have confidence the system will function as intended at the critical moment.

This study examines the factors considered, the approaches taken and the outcomes in the design and this study examines the factors considered, the approaches taken and the outcomes in the design and implementation of a real time acquisition system for the Israeli National EEW Network, TRUAA.

Pyrocko—A Versatile Software Framework for Seismology

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Pyrocko is an open-source seismology toolbox and Python library available for Linux, Windows and Mac. It can be utilized flexibly for a variety of geophysical tasks, like seismological data processing and analysis, modeling of waveforms and displacements from InSAR or GPS displacement data, or for seismic source characterization. At its core, Pyrocko is a library and framework providing building blocks for researchers and students wishing to develop their own applications.

Pyrocko contains standalone applications for everyday seismological practice. These include the Snuffler graphical user interface, an extensible seismogram browser and workbench, the Cake tool, providing travel-time and ray-path computations for 1D layered Earth models, Fomosto, a tool to manage pre-calculated Green's function stores, Jackseis, a command-line tool for common waveform archive data manipulations, and Colosseo, a tool to create synthetic earthquake scenarios, serving waveforms and static displacements. In this presentation, we want to provide an overview and introduction to Pyrocko's features, focusing on standard seismological workflows and teasing the power modular building blocks.

Pyrocko—The Other Seismology Toolbox in Python

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Pyrocko is an open-source seismology toolbox and Python library available for Linux, Windows and Mac. It can be utilized for various geophysical tasks, like seismological data processing and modeling of seismic waveforms or displacement data from InSAR and GPS displacement data. At its core, Pyrocko is a library and framework providing building blocks for researchers and students wishing to develop their own applications and share them with the research community. Apart from fundamental functions for data reading, manipulation and writing, Pyrocko ships with an extensible seismogram browser and workbench, allowing convenient data handling in a graphical user interface.

Pyrocko contains standalone applications for everyday seismological practice, which we will present in an additional talk. This poster provides an overview of Pyrocko's features and its extensive ecosystem, including, e.g., probabilistic source inversion (Grond / BEAT), seismic data quality control (AutoStatsQ), waveform-based clustering (Clusty), earthquake detection and location (Lassie) and source-specific station corrections (SCOTER). The poster intends to allow interested seismology students and researchers to meet contributors and users from the Pyrocko community in person at the conference.

QuakeSaver: Smart Seismic Sensors and Fleet Management

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Advances in embedded platforms, sensor technology and real-time network communication enable smart, reliable and scalable seismic network deployments. QuakeSaver seismic sensors leverage these technologies for processing meaningful seismic data products on the sensor and remote management of individual sensors and the network. We present an innovative sensor software stack which moves signal processing routines to the field, enabling real-time analysis of the seismic data stream on the sensor. In addition to that the system implements existing data exchange protocols commonly served by data centers around the world such as FDSNWS or Seedlink. On-device processing routines include continuous calculation of PPSD, analysis of H/V and P wave identification and characterization by neural networks. The processed high-level seismic data products are communicated to data centers in real-time and can be integrated into meaningful hazard mapping, structure change detection or models of rapid loss assessment.

QuakeSaver sensors are developed for native connectivity, highest operating reliability and ease of deployment. The sensor system follows the digital twin paradigm and offers complete remote monitoring and configuration capabilities. It follows best security practices to enable long-lived remote installations with almost zero on-site maintenance requirements.

Swiss Shakemap at Fifteen: Distinctive Local Features and International Outreach

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The Swiss Seismological Service (SED; www.seismo.ethz.ch) at ETH Zürich is the agency in charge of monitoring the seismicity in and around Switzerland and of informing the public, the authorities and the media about earthquake locations, magnitudes and possible impacts. Among the SED earthquake products is ShakeMap (usgs.github.io/shakemap), in use in Switzerland for about 15 years. The Swiss ShakeMap framework has been regularly updated since the original implementation to exploit and integrate the latest advances in seismic monitoring, seismic hazard and engineering seismology at the SED, as well as core software improvements. In this contribution we present the latest developments in, and the outlook for, SED ShakeMaps (SED_SM). SED_SM are constrained by the real-time records of 450+ permanent and temporary stations acquired by the SED (the permanent national CH network, doi.org/10.12686/sed/networks/ch, presently comprises ~220 operational stations), driven by earthquakes identified and characterized using SeisComP (www.seiscomp.de). Event and waveform parameterization is performed using the software module *scwfparam*, part of the free open-source SeisComP distribution. SED_SM use Swiss-specific ground-motion models included in OpenQuake (platform.openquake.org) and high-resolution site amplification models that allow reliable predictions of ground shaking across the Swiss alpine and foreland regions. Automatically collected and processed felt intensities are overlain on SED_SM for comparison though currently these are not automatically integrated in the calculations. For internal SED use, SED_SM provides input to estimate the likelihood of earthquake-triggered mass-movements for significant events (M4.5+). There are plans to include rapid finite-fault information in SED_SM, provided by the FinDer algorithm already operating in real time at SED. The SED is a core founder and contributor of the European ShakeMap initiative (shakemapeu.ingv.it) that promotes international collaboration and harmonization of ShakeMap procedures in the greater European region.

System Monitoring During Stressful Times

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As the number of stations and the complexity of a Regional Seismic Network (RSN) increase, automated monitoring of network components becomes more important. The Southern California Seismic Network (SCSN) uses many specialized software tools to achieve its monitoring requirements for its key elements including seismic sensors, field and telemetry equipment, network switches and routers and computer servers. The SCSN has also produced its own computer scripts to perform routine tasks like checking sensor mass positions, station outages, field equipment state of health, data quality, configuration management and security vulnerabilities. Continuously monitoring during regular operations is difficult enough, but during an earthquake or an aftershock sequence, demands on the seismic network can increase dramatically. During increased seismic activity, there can be a surge in network traffic volume due to compression inefficiencies. Shaking-induced equipment failure can trigger dynamic routing changes; monitoring should track and record such changes for future analysis. With remote working conditions imposed by pandemic restrictions, system monitoring is more challenging because of personnel absence in data centers and labs. Earthquake Early Warning (EEW) have brought further monitoring requirements with needs for low latency and complete data streams.

In this session, we will review our current routine monitoring tools including Nagios, SeisNetWatch (SNW), Cacti, Unimus, NetBox and others, and identify their strengths and limitations. We will share tips and tricks to remotely check monitoring systems. We will also examine the stress brought on to staff due to monitoring fatigue and prioritization practices during multiple failures. We will discuss innovative monitoring tools and scripts we are investigating. We will further discuss our goal to improve and consolidate the many different monitoring tools and scripts we currently use.

The Advanced National Seismic System ComCat Earthquake Catalog: Nine Years of Amassing Earthquake Source Parameters and Impact Data

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The U.S. Geological Survey (USGS) maintains the Advanced National Seismic System Comprehensive Catalog or "ComCat". ComCat is a repository of earthquake bulletins (locations, phase data, magnitudes and moment tensor solutions) and higher-level products including earthquake finite-fault models, "Did You Feel It?" reports, ShakeMap ground motion estimates, PAGER impact estimates, ShakeAlert post-alert summaries, ground-failure estimates and tectonic summaries. Most of the U.S. earthquake source parameters are contributed by USGS-supported regional seismic networks. Global earthquakes come primarily from the International Seismological Centre-Global Earthquake Model (ISC-GEM) catalog and the USGS National Earthquake Information Center's Preliminary Determination of Epicenters (PDE) bulletin that, in turn, contain contributions from many non-U.S. networks. Since its creation in 2013, ComCat has expanded by integrating global and regional earthquake bulletins and supporting higher-level products. Presently, ComCat contains hypocentral information for about 4 million earthquakes, ~41,000 moment tensors, ~28,000 ShakeMaps, ~7,200 PAGER results and 224 finite fault models. In our presentation, we provide an overview of ComCat contents and tips for accessing the data. We show how ComCat completeness improves over time for different regions and summarize the contents of the major contributing catalogs. We also present a description of the tools and semi-automated quality-control procedures developed to uncover errors including systematic magnitude biases, missing time periods, duplicate event postings and incorrectly associated events. Finally, we provide information on future ComCat developments designed to improve the quality, content, utility and accessibility of the repository.

The Colorado Geological Survey Seismic Network, Collaboration and Outreach

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The Colorado Geological Survey Seismic Network (CGSSN) began with the adoption of four former Transportable Array stations. Since then, four additional permanent stations have been installed throughout the state. To date, the primary focus of the CGSSN is to assist in the monitoring and locating of small magnitude natural and induced events. We will be presenting the current status of the CGSSN including its equipment, our goals for the future of the network and the lessons we have learned. We will present our proposed locations for new permanent stations and are hoping to get feedback from the community on those locations and other ways we might be able to make the CGSSN provide the greatest scientific service possible. Outreach and collaboration are some of our top priorities and we will discuss how the CGSSN has fostered collaborations with other research and educational institutions, outreach opportunities and interactions with the community as a whole.

The Community Seismic Network (CSN): 1000 Stations in the Los Angeles Basin

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The CSN is currently a network of over 700 low-cost accelerometers located in the Los Angeles area that is scheduled to grow to over 1000 in the near future. Its primary goal is to capture the strong motions of earthquakes in order to rapidly assess the damage and provide a spatially dense set of observations for ground motion prediction simulations. There are currently over 400 stations located on the Los Angeles Unified School District campuses that cover the northern part of the LA Basin. This will soon be expanded to 700 stations, which will monitor the central LA Basin. In addition, we have dense arrays (at least one sensor per floor) in several buildings that are 52, 15, and 10 stories to monitor their state of health. We also have over 200 instruments on the JPL campus to provide a testbed of a densely instrumented city.

The sensors consist of a three-component MEMs accelerometer coupled with a micro-computer (Raspberry-Pi), which provides edge computing for signal processing and event detection. The data are recorded on-site and are sent to the Amazon cloud every ten minutes. Detections and associated data are sent immediately with latencies that are typically a few milliseconds, thus making the network suitable for Earthquake Early Warning. The sensors will stay on-scale for accelerations up to 2*g* and are sufficiently sensitive to detect M3 events anywhere in the LA Basin. The CSN has shown that accelerations in the LA Basin vary significantly on a kilometer scale in a manner that the SCSN or current strong motion networks do not capture. Data from the CSN for significant earthquakes is available from the CSN website (http://csn.caltech.edu/).

Use of the SCARDEC Method for Monitoring and Research Applications

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Using teleseismic body waves, the SCARDEC method (Vallée et al., GJI, 2011) provides simultaneous access to some classical earthquake parameters (moment magnitude, depth, focal mechanism) and to the Source Time Functions (STFs). With a magnitude threshold at 5.5-6, about 200 earthquakes are characterized each year with this approach, which highly relies on the Earth coverage provided by the global-oriented broadband seismic networks (in particular GSN, Geoscope and Geofon). Since 2014, SCARDEC has been implemented in near-real time by the Geoscope Observatory with the help of the IPGP data center. Solutions are determined ~45 minutes after origin time and disseminated through the Geoscope website, mailing lists and twitter (account @geoscope_ipgp).

This presentation first reviews the interests of the SCARDEC information for monitoring purposes. Based on comparisons with other methods (in particular GCMT), it will be shown that first-order source parameters determined in near-real time are robust, which gives additional confidence to the STF determinations. STFs themselves are useful to rapidly detect uncommon and possibly hazardous earthquakes, such as multi-source or tsunamigenic events. Besides monitoring, STFs also provide valuable information for the analysis of the seismic source process, which motivated the constitution of an STF database gathering all the earthquakes since the beginning of the 1990's (Vallée and Douet, PEPI, 2016; http://scardec.projects.sismo.ipgp.fr/). This database currently has close to 4000 earthquake STFs, allowing for exhaustive analyses of the source process. Systematic STF determinations are finally useful for structure studies requiring waveform modeling at periods shorter than the source duration.

Visualizing Global Seismic Phases With AlpArray

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Seismic wave propagation is intrinsically a process in time and space. Although seismometers make point measurements only, dense, large-aperture seismic networks allow the full observation and analysis of wave propagation. We present a new visual representation of teleseismic seismic phases by combining time-dependent ground-motion visualizations with array analyses to connect the time-domain motion with phase information retrieved from the frequency–wavenumber (*f-k*) domain. This serves as an educational tool, but also for efficient identification of off-angle arrivals, dispersion and anomalous seismic phases. The processing is applied to events with $M_W \geq 7$ observed at the AlpArray Seismic Network in Europe, a large-scale multidisciplinary seismic network in Europe that consists of over 600 3-component broadband stations with a mean inter-station distance of 30-40km. We will highlight some interesting observations in the visualization of a few example events.

New Developments in Physics- and Statistics-based Earthquake Forecasting

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); William H. Savran, Southern California Earthquake Center (wsavran@usc.edu); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch)

Space-time Variations of Seismicity: Quantitative Assessment and Systematic Changes Before Large Earthquakes

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We discuss recent results aimed at robust identification and quantification of space-time variations of earthquakes with the ultimate goal of tracking preparation processes of large earthquakes. The first part focuses on progressive localization of seismicity, which corresponds to mechanical evolution of deformation from distributed failures in a rock volume to localized shear zones, culminating in generation of primary slip zones and large earthquakes. We present a methodology for estimation of localization using earthquake catalogs and acoustic emission experimental data and showcase its applications to tracking localization processes of large failure events. This analysis is performed with declustered catalogs. The second part describes a technique to assess the degree of regional clustering of earthquakes and justifies the need for declustering in localization and other analyses of seismicity. We demonstrate that events included in the existing short-duration instrumental catalogs are concentrated strongly within a very small fraction of the space-time volume, which is highly amplified by activity associated with the largest recorded events. The earthquakes that are included in instrumental catalogs are unlikely to be fully representative of the long-term behavior of regional seismicity, creating a bias in a range of seismicity analyses. Methodologically, both discussed topics are based on using the Receiver Operating Characteristic (ROC) framework. We demonstrate how this unified framework is adopted for diverse tasks, including assessment of coupled space-time clustering after controlling for space and time marginal inhomogeneities of earthquake rates and tracking time-dependent transformations of a highly inhomogeneous earthquake space distribution. The examined data include crustal seismicity in California, Alaska and other regions, synthetic catalogs of the ETAS model and acoustic emission data of laboratory fracturing experiments.

A b-value Based Analysis of Earthquake Sequences for Japan Using Deep Learning

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The b-value from the Gutenberg-Richter relation captures the ratio between small and large earthquakes triggering for a region. Several researchers have observed fluctuation in b-values prior to an earthquake especially during the aftershock sequence analysis. By leveraging the ever-increasing earthquake database and the development in the field of deep learning computations, this study focuses on analyzing the spatial-temporal b-value series for Japan.

We follow a two step approach, in the first step a spatial-temporal b-value series is calculated from the earthquake catalog, which takes the shape of a series of [32 × 32] pixel images of spatial b-value distributions. On this we train an autoencoder, which compresses and then decompresses the input to learn the normal behavior and relationships within the data. In the second step, we then take the pixel by pixel reconstruction error as input for a Dilated ResNet-like classifier, which predicts an earthquake probability. We expect that this study will improve the understanding of earthquake occurrences which could further be beneficial for Early Warning, rapid response and mitigation plans, especially for sustainable human habitats in earthquake-prone regions.

Physical Properties of the Crust Influence Aftershock Locations

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Aftershocks do not uniformly surround a mainshock, and instead form spatial clusters. Spatially-variable physical properties of the crust may influence this distribution of aftershocks. I study four aftershock sequences in Southern California (1992 Landers, 1999 Hector Mine, 2010 El Mayor-Cucapah and 2019 Ridgecrest) to investigate which physical properties are spatially correlated with aftershock occurrence. I find that aftershock spatial density exhibits an order of magnitude or more variation as a function of several properties. Multiple measures of the mainshock static stress change (including Coulomb stress change and stress similarity) correlate with aftershock occurrence. Aftershock rates correlate with fault structure and kinematics, decaying with distance from the nearest mapped fault and increasing with strain rate. The aftershock rate scales with the background seismicity rate, but not as strongly as predicted by the Coulomb Rate and State model. Aftershocks preferentially occur in locations with mid-range values of heat flow and seismic velocity. I determine simple empirical relations between each of these properties and the aftershock spatial density, and use these relations to construct new spatial models of aftershock locations. The new spatial models are a significant improvement over the base model, which includes only the well-known decay of aftershock rate with distance from the mainshock, but do not fully capture the dense spatial clustering of aftershocks. Numerous spatially-varying physical properties exhibit no (or poor) correlation with aftershock spatial density, including temperature, rock composition, and rheological properties that might be expected to control aftershock occurrence. These results yield empirical relationships between spatially-variable physical properties and aftershock locations, but more work is necessary to understand the physical processes that link aftershock occurrence to these physical properties.

Does Abundant Afterslip Mean Productive Aftershock Sequences?

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Many studies suggest that aseismic afterslip plays a key role in driving aftershock sequences, often citing strong correlations in their spatio-temporal evolutions. In a previous work, we showed that the amount of afterslip produced after an earthquake can vary greatly, from <1% to >300% of the coseismic moment. Thus, afterslip could feasibly account for some of the spatio-temporal complexity many aftershock sequences exhibit, which coseismic Coulomb static stress change alone struggles to explain. If this link is robustly established, including afterslip in frameworks such as ETAS (which currently assumes that every earthquake triggers aftershocks in a statistically identical way) may improve their predictive capabilities.

We explore correlations between the relative afterslip moment of compiled earthquakes and the relative productivity, relative cumulative moment, b-value and Omori decay exponent (p) of the corresponding aftershock sequences. We select sequences from the global PDE catalog (M_C=4.7) for comparability across different tectonic regions using three methods for robustness: 1) a 2D method based on empirical aftershock-zone scaling; 2) a 3D method using a volume around the ruptured fault planes that afterslip may reasonably activate via static Coulomb stress; and 3) a Nearest Neighbour Distance declustering algorithm. These methods select similar proportions of aftershocks for a given mainshock. Across different mainshocks, variation in the relative productivity and relative cumulative moment of sequences correlates weakly with relative afterslip moment, but b-value and p do not. It is surprising that relative afterslip moment does not correlate with aftershock decay, but we cannot rule out that afterslip decays do not co-vary with aftershock decays globally. However, here we cannot provide strong evidence on these global, statistical scales that afterslip drives aftershocks, but recognise that additional probing of decay behaviours is necessary.

Finding the Next Layer of Seismicity Patterns in High-resolution Catalogs

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The clearest statistical signal in aftershock locations is that most aftershocks occur close to their mainshocks. To first order, aftershocks are triggered at distances following a power-law decay in distance (Felzer and Brodsky, 2006). While individual sequences tend to show clustered aftershock distributions, it is hard to predict the spatial clustering in advance, and the forecast distribution is typically treated as azimuthally isotropic. This distance decay kernel is often used in Epidemic-type Aftershock Sequence (ETAS) modeling. The assumption of spatially isotropic triggering kernels can impact the estimation of ETAS parameters themselves, such as biasing the magnitude-productivity term alpha and assigning too much weight to secondary rather than primary (direct) triggering. Using a novel sorting and stacking method, we show that aftershock locations, at all mainshock-aftershock distances, preferentially occur in areas of previous seismicity, as predicted by rate-and-state friction (Dieterich, 1994). However, on a broader scale, we see only a weak correlation between total aftershock productivity and background rate in California. Areas of low background rate can have both very low and very high aftershock productivity, while areas of high background rate rarely have low aftershock productivity.

How Can Probabilistic Forecasts Learn From Physics-based Simulators? A Full-bayesian Approach to Forecast Recalibration

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A general problem in earthquake forecasting is how to assimilate deterministic physical simulations into probabilistic forecasting models. Here we focus on recalibrating the time-independent Uniform California Earthquake Rupture Forecast Version 3 (UCERF3) of Field et al. (2014) against long earthquake catalogs (~ 10^6 yr) generated by the multi-cycle Rate-State Quake Simulator (RSQSim) of Dieterich & Richards-Dinger (2010). We map RSQSim ruptures from the Shaw et al. (2018) catalog onto equivalent UCERF3 ruptures by maximizing the mapping efficiency while preserving the seismic moment. We assume the sequence of equivalent UCERF3 ruptures is Poisson distributed; i.e., each rupture occurs at a time-independent rate, our knowledge of which is uncertain. We use the full UCERF3 logic tree to construct a joint prior distribution of ruptures rates, which we represent by independent gamma distributions. Updating the UCERF3 gamma priors with the empirical RSQSim rates yields gamma posterior distributions and inverse binomial posterior predictive distributions that can be calculated analytically. We use the latter to test the recalibrated UCERF3 model against an independent RSQSim catalog, assessing its predictive skill relative to the UCERF3 prior model. We discuss how to extend our treatment of time-independent problem to include correlations among event rates using multivariate log-normal distributions, which are not conjugate to Poisson distributions and therefore require numerical calculation of the posteriors. We also briefly address the even more challenging problem of constructing time-dependent forecasts that have been conditioned on knowledge of the previous rupture history over time intervals of the last 100 years or so.

Statistical Analysis of Low-frequency Earthquake Catalogs

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Low-frequency earthquakes are small magnitude (less than 2) earthquakes, with reduced amplitudes at frequencies greater than 10 Hz relative to ordinary small earthquakes. They are usually grouped into families of events, with all the earthquakes of a given family originating from the same small patch on the plate interface and recurring more or less episodically in a bursty manner. In this study, I analyze catalogs of events from several low-frequency earthquake families, located in Cascadia, Mexico and the San Andreas Fault, by translating the catalogs into discrete time series defined by the number of events per unit of time. Long-range dependence is a phenomenon that may arise in the statistical analysis of time series data. It relates to the slow rate of decay of the statistical dependence between two points with increasing time interval between the points. If there is long-range dependence in a time series, even small correlations between two points cannot be neglected to compute the variance of the sample mean for instance. I used several graphical methods to compute the value of the fractional parameter d, which represents how fast the variance in the number of low-frequency earthquakes increases with the length of the time window considered for the aggregation. For most families of the catalogs studied, I find that $0 < d < 0.5$, which is characteristic of long-range dependence in the time series.

My future objective is to model the intensity function associated with each low-frequency earthquake sequence using an epidemic-type aftershock sequence model, or more advanced models like neural temporal point processes or recurrent neural networks. In particular, we need to verify whether this type of models can reproduce the apparent long-range dependence observed in the time series. The statistical characterization of low-frequency earthquake occurrence could provide important constraints on future mechanical models of low-frequency earthquake generation.

Relaxing ETAS's Assumptions to Better Capture the Real Behavior of Seismicity

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When developing next-generation earthquake forecasting models, the key is to more carefully account for the real world (which has fault systems with different properties, site-specific properties, swarm-like episodes of temporally elevated seismicity, etc.), without constructing overly complicated models that are hard to comprehend and even harder to use. Finding the sweet spot between simplicity and accuracy is what constitutes the art of modelling. Epidemic-Type Aftershock Sequence (ETAS) models, despite being introduced over three decades ago, are still the undisputed reference for earthquake forecasting methods—be it as a benchmark when testing novel forecasting techniques, or as the model of choice for operational earthquake forecasting around the world. ETAS models accurately describe the average behavior of aftershock triggering as a self-exciting point-process based on few simple empirical principles, including the Omori-Utsu and Gutenberg-Richter laws.

With this in mind, we are proposing a new model which naturally captures the diversity of conditions under which earthquakes take place. Within the ETAS statistical framework, we relax the assumptions of parametrically defined aftershock productivity and background earthquake rates. Instead, both productivity and background rates re calibrated with data such that their variability is optimally represented by the model. This allows for an impartial view on the behavior of background and triggered seismicity in different regions, different time periods, or different sequences. We perform pseudo-prospective forecasting experiments for Southern California to evaluate models based on their accuracy at forecasting the next event. These experiments reveal when, where, and under which conditions our proposed model yields better forecasts than the standard ETAS null model.

The Neural Temporal Point Process: A Scalable and Flexible Tool for Earthquake Forecasting

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The growth in scale of earthquake catalogs poses a challenge for standard approaches in statistical seismology. However, voluminous new data also presents an opportunity to utilize machine learning approaches. Here we present a scalable and flexible neural model for temporal point processes applied to earthquake forecasting. We show benchmarks of its performance against the widely utilized epidemic type aftershock sequence (ETAS) model using both synthetic and real earthquake catalogs. These indicate that a relatively simple neural network architecture is sufficiently expressive to approximate the underlying structure of a synthetic earthquake data dataset. With real data, the marginal earthquake improves its performance relative to ETAS. The neural temporal point process yields better log-likelihood goodness of fit and intermediate-term forecasts skill on modern earthquake catalogs (>10^4 events). Our results suggest that more general forecasting frameworks can leverage voluminous datasets to generate improved forecasts and physical insight.

Neural-network Based Models for Earthquake Rate Prediction

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Modeling the statistics of earthquake catalogs as point processes is a long tradition in statistical seismology. State-of-the-art models, like ETAS and its variants, learn a handful of parameters from the data and use them in some predetermined simple functional form (e.g.~Omori's law). It is natural to expect that such models, that use human-engineered features, could be improved by using neural networks with their remarkable expressive power and ability to represent complex correlation structures. In this work we incorporate recent methodological advances in Neural modeling of spatiotemporal point processes to create a Neural-Net based earthquake rate predictor. We demonstrate the advantage of our construction over ETAS using strict train-test data splits and show how it opens the door for easily incorporating additional information.

New Developments in Physics- and Statistics-based Earthquake Forecasting

Poster Session · Friday 22 April · Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); William H. Savran, Southern California Earthquake Center (wsavran@usc.edu); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch)

A New Seismic Moment Magnitude (Mwg) and Moment Magnitude (Mw): Common Root and Differences

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Earthquake magnitude scale is one of the most fundamental earthquake source parameters to be used for measuring the strength of an earthquake. Several magnitude scales came into practice for estimating the size of an earthquake where as actual earthquake size remains mostly elusive for many obvious reasons. M_w scale mainly derived and validated for Southern Californian region. Hanks and Kanmori (1979) stated in the abstract Mw is uniformly valid >7.5. Moreover, Mw magnitude scale is defined from very long-period spectral amplitude and is not expected to correlate well with high-frequency ground motion for engineering importance. Therefore, on the basis of 25,708 global earthquake events, a new magnitude scale (Bulletin of Seismological Society of America: 109(4), pp. 1542–1555, August 2019) called seismic moment magnitude scale or Das Magnitude Scale (DMS) denoted by M_{wg} has been determined that closely connected to observe magnitudes scales such as m_b, Ms, Me and radiated energy Es. This study will discuss in details about the common roots and differences between M_w and DMS scales (M_{wg}) and show the impact of incorrect use of Mw scale in earthquake engineering specially in developing seismicity parameters. Furthermore an Mwg based earthquake catalog with 39977 events for period 1516-2016 in magnitude range 1.7–8.8 has been be prepared for Northern Chile and Southern Peru with the help of developing regional scaling relationships between different magnitudes (m_b, M_s, M_L) and M_{wg}. The scaling relationships have been developed following recently suggested error corrected Orthogonal Regression methodology. The details of common roots and differences of the two scales will serve as a guideline for earthquake magnitude study. The prepared Mwg based unified catalog will serve a solid purpose for different seismological applications (e.g., Seismic Hazard Assessment, preparation of GMPE, Seismicity, Seismotectonics and Earthquake Prediction) for the study area.

An Interactive Web Tool to Visualize and Improve USGS Operational Aftershock Forecasts

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The USGS Earthquake Hazards Program provides information to the public when potentially damaging earthquakes happen. The Operational Aftershock Forecasting (OAF) system (https://earthquake.usgs.gov/data/oaf/) publishes the chance of more earthquakes occurring in the next day, week, month and year after all M5+ earthquakes in the US. OAF makes ~5000 forecasts per year. Accuracy is important because the forecasts are used by emergency managers and infrastructure operators to make well-informed decisions, increasing the efficiency of emergency response. The forecasts also help increase public awareness of potential aftershock dangers, such as damaged buildings.

We are building an interactive web tool to visualize aftershock sequences and determine the accuracy of the OAF forecasts. The underlying code will be an open-source R package that interacts with the Comprehensive Earthquake Catalog (ComCat), where OAF stores its forecasts and obtains data to tune its models. The user can choose the area and time period of their interest, query ComCat for earthquakes with forecasts, pull the forecast data and retrieve seismicity in order to visualize and analyze the forecasts interactively via the web tool.

Earthquakes with forecasts are shown on a global map and selecting an earthquake shows the aftershocks on a local map. A magnitude-time scatter plot shows magnitude type and the source network, a line plot compares the cumulative number of aftershocks to the forecast model and a magnitude-frequency plot shows the number of earthquakes of each magnitude. We will also take the forecasts for each sequence and determine what fraction of observations are within the forecasted range. Each plot can be customized based on user choices.

Improving the plots helps seismologists understand the complexities in the data and improve the OAF system by comparing past forecasts to observations. Improved maps help seismologists evaluate the spatial region used for the forecast and improve communication with users. Our R package will help the OAF team maintain operational awareness and provide accurate information to the public.

Assessing the Predictive Skills of Global and Regional Earthquake Forecasting Models for California, Italy and New Zealand

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The increasing availability of geophysical datasets has enabled the creation of global and regional earthquake forecasting models that can underpin probabilistic seismic hazard assessments. Whereas regional models provide detailed seismicity forecasts, global models offer greater testability of the large damaging earthquakes. Here, we prospectively assess the predictive skills of the Global Earthquake Activity Rate (GEAR1) model developed by Bird et al. (2015) and nineteen regionally calibrated models to forecast earthquakes in California, Italy and New Zealand from 2014 through 2021. To this end, we project GEAR1 onto these testing regions defined by the Collaboratory for the Study of Earthquake Predictability (CSEP) and use a set of consistency and comparative likelihood tests implemented in CSEP's Python toolkit pyCSEP. Prospective test results show that, in California, most of the models overestimate the number of earthquakes and incorrectly describe the spatial distribution of seismicity. Additionally, a model that adaptively smoothes the locations of small earthquakes obtains an Information Gain Score per Earthquake (IGPE) of 1.0 over GEAR1. In Italy, all the models forecast rates consistent with the observations and most models can satisfactorily explain the spatial distribution of epicenters. Further, a model that uses adaptively smoothed seismicity obtains an IGPE of 0.6 over GEAR1. Finally, in New Zealand, most models adequately forecast the number and location of observed earthquakes, with GEAR1 obtaining an IGPE of 0.5 over a regional smoothed seismicity model. In the case of New Zealand, these results are mainly due to the fact that GEAR1 includes seismicity information derived from the occurrence of the 2011 Christchurch sequence, which is not present in other models. In the case of California and Italy, comparative test results indicate that the use of small earthquakes adds substantial predictive ability to forecast larger events. Thus, we preliminarily conclude that regional models, which often benefit from small earthquake data, provide more informative seismicity forecasts than global models.

Phebus: A Full Bayesian Workflow to Estimate Earthquake Recurrence Parameters and Uncertainties for Seismic Hazard Models

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We present a python package, called *Phebus*, whose main purpose is to estimate earthquake recurrence parameters and confidence intervals, using a full Bayesian approach, in the framework of probabilistic seismic hazard assessment (PSHA). PSHA is a model-based approach, where seismic source models and ground motion models are combined to predict spectral accelerations in a given site and for a given time period. PSHA is applied for both site-specific evaluation in case of critical facilities (e.g. nuclear facilities) and at national or regional scale for building codes. The procedure adopted in PSHA calculations requires careful considerations, especially for modeling the occurrence of earthquakes in low-to-moderate seismic regions, where seismic events are not necessarily associated to specific faults but distributed over a geographical zone. We then apply our Bayesian method to metropolitan France, characterized by few observed data and high uncertainties with high safety/regulatory constraints to meet. We compare our results with other current methodologies used for calculating the earthquake recurrence parameters and quantify their impact on the level or shape of the hazard curves for different French sites.

Moreover, several choices of area source models and ground motion models are typically available and compose the PSHA logic-tree to propagate epistemic uncertainties, despite expert judgments. In Phebus, model weights can be updated given available data (earthquake catalogs, accelerometric recordings) combined in a Bayesian model averaging approach. We identify and correct certain flaws of existing methods, yielding a more rigorous way to process the data, with the potential of reducing prediction uncertainties, as demonstrated through some applications to the French context.

pyCSEP: A Python Tool-kit for Earthquake Forecast Developers

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The Collaboratory for the Study of Earthquake Predictability (CSEP) is an open and global community whose mission is to accelerate earthquake predictability research through rigorous testing of probabilistic earthquake forecast models and prediction algorithms. pyCSEP is a software toolkit that provides open-source implementations of useful tools for evaluating earthquake forecasts. pyCSEP contains the following modules for working with probabilistic earthquake forecasts: (1) earthquake catalog access and processing, (2) representations of probabilistic earthquake forecasts, (3) statistical tests for evaluating earthquake forecasts and (4) visualization routines and various other utilities. Most importantly, pyCSEP contains several community-endorsed implementations of statistical tests needed to evaluate earthquake forecasts. pyCSEP can evaluate two types of forecasts: those expressed as expected rates in space-magnitude bins and those specified as sets of simulated catalogs (including candidate models for governmental Operational Earthquake Forecasting). Current efforts include expanding the forecasting class to forecasts defined on quadtree grids, adding evaluation methods such as binary likelihood scores and receiver operating characteristics, including new visualization routines, incorporating a global earthquake reference model and developing a module of earthquake declustering algorithms. We are proud to note that many of these contributions came from members the community. To help new users get familiar with the code and learn the contribution process, we provide several working examples and pages of documentation at https://docs.cseptesting.org. The software can be found on GitHub at https://github.com/SCECCode/pycsep. Our intention is that providing useful tools to earthquake forecast modelers and facilitating an open-source software community will broaden the impact of CSEP, further promote earthquake forecasting research and assist in the development of seismic hazard products.

Ranking Earthquake Forecasts Using Proper Scoring Rules: Binary Events in a Low Probability Environment

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Operational earthquake forecasting for risk management and communication during seismic sequences depends on our ability to select an optimal forecasting model. To do this, we need to compare the performance of competing models in prospective experiments, and to rank their performance according to the outcome using a fair, reproducible and reliable method, usually in a low-probability environment. The Collaboratory for the Study of Earthquake Predictability (CSEP) conducts prospective earthquake forecasting experiments around the globe. One metric employed to rank competing models is the Parimutuel Gambling score. We examine the suitability of this score for ranking earthquake forecasts. We prove analytically that this score is in general 'improper', meaning that, on average, it does not prefer the data generating model assuming this is known. In the special case where it is proper, we show it can still be used improperly. We compare its performance with two commonly-used proper scores (the Brier and logarithmic scores) using confidence intervals to account for the uncertainty around the observed score difference. We think that using confidence intervals enables a rigorous approach to distinguish between the predictive skills of candidate forecasts in addition to their rankings. Our analysis shows that the Parimutuel Gambling score is biased, and the direction of the bias depends on the forecasts taking part in the experiment. Our findings suggest the Parimutuel Gambling score should not be used to distinguish between multiple competing forecasts, and for care to be taken in the case where only two are being compared.

Numerical Modeling in Seismology: Developments and Applications

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Alice-Agnes Gabriel, Ludwig-Maximilians-University of Munich (alice.gabriel@web.de); Wei Zhang, Southern University of Science and Technology Shenzhen (zhangwei@sustech.edu.cn); Emmanuel Chaljub, Université Grenoble Alpes (emmanuel.chaljub@univ-grenoble-alpes.fr); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov)

A Discontinuous Galerkin Method for Sequences of Earthquakes and Aseismic Slip on Multiple Faults Using Unstructured Curvilinear Grids

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Simulations of sequences of earthquakes and aseismic slip (SEAS) including more than one fault and complex geometries are challenging. We present a symmetric interior penalty discontinuous Galerkin (SIPG) method accounting for the complex geometries and heterogeneity of the subsurface. The method accommodates two- and three-dimensional domains, is of arbitrary order, handles sub-element variations in material properties and supports isoparametric elements, i.e. high-order representations of the exterior and interior boundaries and interfaces including intersecting faults. We provide an open-source reference implementation, Tandem, that utilises highly efficient kernels, is inherently parallel and well suited to perform high resolution simulations on large scale distributed memory architectures. Further flexibility is provided by optionally defining the displacement evaluation via a discrete Green's function, using algorithmically optimal and scalable sparse parallel solvers and preconditioners.

We highlight the characteristics of the SIPG formulation via an extensive suite of verification problems (analytic, manufactured and code comparison) for elasto-static and seismic cycle problems. We demonstrate that high-order convergence of the discrete solution can be achieved in space and time for elasto-static and SEAS problems. Lastly, we apply the method to realistic demonstration models consisting of a 2D SEAS multi-fault scenario on a shallowly-dipping normal fault with four curved splay faults and a 3D multi-fault scenario of instantaneous displacement due to the 2019 Ridgecrest, CA, earthquake sequence. We exploit the curvilinear geometry representation in both application examples and elucidate the importance of accurate stresses (or displacement gradients) representations on-fault. Our results exploit advantages of both the boundary integral and volumetric methods and is an interesting avenue to pursue in the future for extreme scale 3D SEAS simulations.

The Finite-difference Modeling of Seismic Waves in Media With Poroelastic/Elastic Interfaces

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Real surface or near-surface Earth structures consist of viscoelastic sediments, porous rocks and fluids, often in complex geometrical configurations. It is well known that the earthquake ground motion can be significantly amplified and prolonged in surface sedimentary basins. Those often include an air- and water-saturated sediments. Effects of poroelasticity on earthquake ground motion in geometrically realistic configurations of surface sedimentary basins have not been sufficiently investigated. It is therefore desirable to have a numerical scheme capable of modelling seismic waves in realistic models consisting of viscoelastic solids, poroviscoelastic rocks and fluids.

As the first step, we present a new methodology of the finite-difference (FD) modelling of seismic wave propagation in a strongly heterogeneous medium composed of poroelastic and strictly elastic parts. The medium can include poroelastic/poroelastic, poroelastic/elastic and elastic/elastic material interfaces of arbitrary shapes. The poroelastic part can be with a) zero resistive friction, b) non-zero constant resistive friction or c) JKD model of the frequency-dependent permeability and resistive friction. Our FD scheme is capable of sub-cell resolution: a material interface can have an arbitrary position in the spatial grid. The scheme keeps computational efficiency of the scheme for a smoothly and weakly heterogeneous medium (medium without material interfaces). We numerically verified our FD modelling against independent analytical, semi-analytical and spectral-element methods. The numerical tests prove the efficiency and accuracy of our FD modelling. In numerical examples we indicate effect of the poroelastic/elastic interfaces for a constant resistive friction and a frequency-dependent permeability and resistive friction. We address the 2D P-SV problem. The approach can be readily extended to the 3D problem. The approach will be generalized for accounting a realistic viscoelasticity.

3D Simulation of Seismic Response of the Long Valley Embankment Dam, California

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Assessment of seismic hazard for embankment dams is crucial since they are typically built from compacted soils and rocks, which make them more prone to failure than concrete dams during strong ground shaking. As a case study, we conducted 3D 0-7.5 Hz deterministic wave propagation simulations to model realistic seismic response of the Long Valley Dam (LVD) in Central California using the discontinuous-mesh, fourth order accurate finite difference code AWP-ODC. Our goal is to account for the nonlinear effects in the time domain in order to adequately describe the complete seismic response of the dam during the extended duration of ground motions generated by large earthquakes. As the first step, we calibrated the velocity structure, anelastic attenuation model and the overall properties of the dam by performing linear simulations of an Mw 3.7 event using a point source. In our validation work we showed that accurate near-surface geotechnical layers are crucial to match observed ground motions at high frequencies (above 1Hz). A homogeneous model of the compacted dam core is sufficient for reproducing seismic waveforms observed right on the dam structure. A velocity-dependent attenuation model of Qs=0.075Vs, Qp=2Qs with a power law exponent of 0.2 for the frequency dependence best describes the observed spectral characteristics and coda wave amplitudes. With the calibrated model, we simulated the 1986 Mw6.3 Chalfant Valley earthquake, located 30 km from the LVD, using a finite-fault source description. Our simulations produced waveforms similar to the observations, with minimal nonlinearity needed around the LVD. Finally, we will present results of nonlinear simulations of Mw6.6 Maximum Credible Earthquake scenarios on the Hilton Creek fault, located within 10 km of the LVD.

An Improvement of Corner-frequency Modeling for Stochastic Finite-fault Ground Motion Simulation

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Stochastic finite-fault ground motion simulation is widely used in various scientific and engineering applications. However, the current theoretical modeling of the corner-frequency used in the source spectrum model, which controls the ground motion level at high frequencies, is problematic because it does not consider the impact of rupture velocity. This study provides a modification of the current corner-frequency modeling and establishes a correlation between corner-frequency and rupture velocity, making the source spectrum model more theoretically consistent. An additional inspection of the rise-time model is also provided in this study, and the application appropriateness of the widely used rise-time model is discussed. A detailed comparison between the updated corner-frequency model and the currently used model (embodied in EXSIM) is provided. For validation purposes, the updated corner-frequency and rise-time model is applied to predict the ground motions on rock sites during the 2012 M_L5.4 Moe earthquake that occurred in southeastern Australia and the 2014 M_S6.5 Ludian earthquake that occurred in southwestern China. The results show that the updated model is reliable for providing more accurate estimates of corner-frequency, rise time and ground motion amplitudes with smaller average residuals than the currently used model. Furthermore, an enhanced MATLAB-based software program package (namely GMSS2.0) is provided for implementing stochastic finite-fault ground motion simulations, with an option to use the currently used corner-frequency model and the updated one proposed by this study. GMSS2.0 is validated by comparing the simulations with five NGA-West2 Ground Motion Models (GMMs) for multiple scenario earthquakes with the updated site amplification for the generic California condition (V_{S30} = 500 m/s).

How Does Spatial Variability of Soil Properties Affect Seismic Response of Slopes?

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When elastic shear waves impinge on a homogeneous sloped ground, reflections of both mode preserving and converting types take place to satisfy the traction-free boundary condition along the surface. Furthermore, points of discontinuity, like the toe and tip of the slope, act as secondary virtual sources to generate a complex diffracted wavefield. Therefore, various converted body and surface waves interfere with the incident and reflected waves. The interaction gives rise to a non-uniform surface response along the slope. Properties of subsurface layers vary spatially even within apparently homogeneous soil strata because of geological deposition and post-deposition processes. In this study, we use a random field finite volume technique to determine the extent to which the inherent spatial variability of soil properties alter the seismic response of slopes. The spatial variability of shear wave velocity and Poisson's ratio of soil are separately modeled as two-dimensional Gaussian random fields using an exact matrix decomposition technique for irregularly shaped media. To present the results in a generalized form, correlation lengths in the horizontal and vertical directions are both normalized with respect to the dominant wavelength of the incident wave. For a set of normalized geometric and material properties and a sufficiently large number of random filed realizations, we calculate the surface ground motion along the slope due to incident seismic waves of various frequency contents. The coefficient of variation of results reflects the degree of uncertainty introduced by the inherent spatial variability of soil properties. The proposed "statistically homogeneous field" approach could also be used to capture other sources of uncertainty in soil properties, such as the scarcity of test data and the resultant interpretation errors and provide more realistic predictive models for ground motion.

Can Higher-order Finite-difference Operators Be Applied Across a Material Interface?

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The finite-difference (FD) method is one of the most important and used methods for numerical simulations of seismic wave propagation and earthquake ground motion in realistic models of surface and near-surface Earth's structures. Grid dispersion is an important factor of the overall accuracy and computational efficiency of the FD modeling. Therefore, FD modelers have been developing sophisticated higher-order schemes in order to reach a desired accuracy both in time and space and in all propagation directions with a larger grid spacing and a larger time step. A larger grid spacing means nothing less but a smaller number of grid spacings per minimum wavelength that is to be propagated in the grid with sufficient optional accuracy. Historic approximations of a spatial derivative itself were independent from the governing equations and thus independent of temporal derivative. Recent approximations are found in the time-space domain for specific governing equations. While it is obvious that higher-order schemes significantly reduce grid dispersion in smoothly and weakly heterogeneous medium, the question is whether they can be equally usefully applied in medium with strong material interfaces. Can a long FD operator be applied across a material interface with strong velocity contrast? This is an important question to be addressed and answered. This is because the accuracy and computational efficiency of FD modeling is important mainly in structurally complex realistic models, that is models that could include strong material interfaces. This is the case, e.g., of the surface sedimentary basins and valleys embedded in bedrock. These sites are capable of producing anomalous earthquake ground motion.

We present results of our parametric investigations of applications of FD operators across material interface in models with exact and approximate representations of material interfaces in a spatial staggered grid.

Numerical Modeling of Earthquake Ground Motion in Georgia Basin Resulting Amplification and Elongation of Events Duration, Greater Vancouver Area, British Columbia

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A finite difference model of wave propagation resulted from crustal ground motion has been developed to estimate ground motion time series and the effects of Georgia Basin in Greater Vancouver Area, British Columbia, Canada. The earthquakes are assumed to occur at the Cascadian Subduction Zone and event amplification and occurrence of the elongation of incident are shown to be considerably longer in Georgia basin.

A synthetic time series of five superimposed sinusoidal regular waves is assumed to occur at the Cascadia Subduction Zone in the vicinity of Southern Vancouver Island and different velocities for propagation of seismic waves along the lower Georgia Basin are assumed. The predicted by the model shows that not only will amplification occur during the motion, but also the amplified shakes can significantly damage the structures built on such low velocity zones due to elongation of ground motion. Moreover, we studied the effect of presence and non-presence of basin has been compared in this study. Here we aim for qualitative effects of presence of such low velocity zones and will be followed by quantitative approaches in future study.

Simulation of Underground Chemical Explosions in Soft Alluvium, Hard Granite, Brittle Tuff and Salt Formations Using Anisotropic Hydrodynamic Generated Source Coupled to Linear Anisotropic Wave Propagation

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The Source Physics Experiment (SPE) is an ongoing effort to improve explosion monitoring by conducting a controlled series of chemical explosions at the Nevada National Security Site (NNSS) and using the resulting observations to improve and validate physics-based simulations of explosion phenomena. Phase I of SPE was conducted on the Climax Stock granite which contains a network of well-characterized joints. It has been shown through hydrodynamic source modeling that sliding on these pre-existing joints may be responsible for a large amount of the tangential motion observed during SPE. Near-field motions generated with hydrodynamic non-linear source models have been coupled to elastic wave propagation codes to propagate these resulting motions into the far-field domain which is assumed to be elastic.

In the present study we use a hybrid modeling approach with one-way hydrodynamic-to-elastic coupling. Near source hydrodynamic motions are computed using GEODYN/L while anisotropic elastic wave propagation is modeled using SW4, a fourth order finite difference code. Motions are coupled between the two codes by introducing hydrodynamic motions from GEODYN/L as a two-shell internal boundary source to SW4. The anisotropic material model employed in the SW4 domain is derived from the properties of an observed fracture network with relatively well-constrained joint orientations, spacing, and stiffnesses. We show that consideration of anisotropic material in the elastic regime has an important effect on the propagation of tangential motion. Propagation of motions generated in an anisotropic source region into an isotropic far-field domain will introduce some biases. To illustrate the versatility of the proposed approach, the current GEODYN/L/SW4 coupling has also been applied to model Phase II of SPE, conducted in a dry alluvium geology (DAG) and it is being extended to consolidated pyroclastic or volcaniclastic rocks such as tuffs. Simulation results from anisotropic alluvium, granite and tuff will be presented.

Seismic Response of Metamaterials Using the Indirect Boundary Element Method for SH Waves in 1D and 2D

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Seismic metamaterials, inspired by the electrical and electromagnetic counterparts, are being studied for a variety of applications as they may exhibit properties that emerge from their structure. For instance, diverse arrays of resonators are aimed to isolate civil constructions from incoming seismic waves during the occurrence of an earthquake. Currently, metamaterials are defined as periodic structures, composed of cells of different materials that exhibit unconventional properties. Mainly, the design of metamaterials is of great relevance in the field of seismology and their main objective is to channel or minimize the amplitude of elastic waves at a given frequency. In this work, we simulate the propagation of SH waves in 1D-2D for periodic structures with cells of different metamaterials. This modeling was carried out using the Thomson-Haskell propagation matrix formulation for the 1D stratified systems and the indirect boundary element method (IBEM) for the 2D case. Furthermore, we performed a parametric analysis of the dynamic properties observing a direct relationship between the bandgap and the dynamic properties of metamaterials. Finally, we find that in 1D, the central frequency of the bandgap is directly proportional to the wave speed and inversely proportional to the thickness of the metamaterials. On the other hand, in 2D, the attenuation of the elastic field is generally more localized and sensitive to more parameters.

Numerical Modeling in Seismology: Developments and Applications

Poster Session · Wednesday 20 April · Conveners: Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Alice-Agnes Gabriel, Ludwig-Maximilians-University of Munich (alice.gabriel@web.de); Wei Zhang, Southern University of Science and Technology Shenzhen (zhangwei@sustech.edu.cn); Emmanuel Chaljub, Université Grenoble Alpes (emmanuel.chaljub@univ-grenoble-alpes.fr); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov)

A New Approach to Estimate a Mixed Model-based Ground-motion Model Using a Computational Optimization Algorithm

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In this study, we employed a metaheuristic algorithm (MA) to optimize the coefficients of a mixed model-based ground-motion model (GMM) with several variance components. The optimization algorithm used here is particle swarm optimization (PSO) that can compute regression coefficients and associated uncertainties of the GMM by considering a one-stage maximum likelihood framework. This framework considers the random-effects model to regression analyses to estimate the parameters in the ground motion models. We used a complex predictive equation to examine whether the proposed optimization algorithm can accurately estimate the regression coefficients and variance components. Coefficients and variance components of the functional form of the predictive equation are estimated and compared with those determined by previous conventional algorithms. To show the accuracy of the proposed methods, extensive verifications are applied to investigate whether the proposed algorithms provide a good accuracy of the dataset from Taiwan used by Chen and Tsai (2002). We determined error metrics and correlation coefficients for the predicted data that show the proposed algorithm provides better results in predicting the data compared to previous approaches in the literature.

An Efficient ADER-DG Scheme for Simulation of Seismic Waves in Poroelastic Media

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Equation of motion for poro-elastic medium derived following Biot's theory contains a stiff reactive term that poses a key computational challenge for numerical methods. We present an efficient ADER-DG scheme (discontinuous Galerkin scheme with Arbitrary high-order DERivative time stepping) for solving problems with the stiff term utilizing a novel block-wise back-substitution algorithm. For polynomials of degree 6, the number of floating-point operations is reduced by a factor of 25 compared to standard LU decomposition. Additionally, the block-wise back-substitution is mapped to a sequence of small matrix-matrix multiplications, for which code generators are available to generate highly optimised code. This way, we achieve excellent node-level performance.

We verify the new scheme thoroughly against (semi)analytical or numerical reference solutions in canonical problems of increasing complexity using a point source. Additionally, we demonstrate that by utilizing a clustered local time stepping scheme, time to solution is reduced by a factor of 6 to 10 compared to global time stepping. We conclude our study with a scaling and performance analysis on the SuperMUC-NG supercomputer, demonstrating our implementation's high computational efficiency and its potential for extreme-scale simulations.

Efficient Quasi-dynamic Simulations of Earthquakes and Aseismic Slip Including Off-fault Viscoelastic Deformation Using Hierarchical Matrices

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The interplay between localized fault slip and distributed viscoelastic deformation within the crust and upper mantle has substantial implications for the loading of stress on faults, the depth-extent and recurrence of earthquake ruptures and the overall state of stress within the lithosphere. However, explicitly incorporating inelastic off-fault deformation into long-term numerical simulations of sequences of earthquakes and aseismic slip (SEAS) remains challenging. Analytic solutions for the stress field due to distributed deformation allow for the efficient inclusion of bulk deformation in SEAS simulation using the integral method, which involves taking the product between a matrix of Green's functions and a deformation vector (Lambert & Barbot, GRL 2016; Barbot GRL 2018). In standard boundary integral methods (BIM), the number of calculations necessary scales quadratically with the number of computational elements, limiting the feasibility of larger-scale simulations. A number of studies have examined avenues for improving the efficiency of the boundary integral method, including the use of hierarchical matrices as sparse approximations of the stress kernel. Here, we compare a hierarchical matrix SEAS simulation that includes viscoelastic deformation to a dense BIM implementation considering the same physical problem. Our ultimate goal is to facilitate the consideration of bulk viscoelastic deformation in larger-scale studies of long-term fault processes, including 3D SEAS simulations with 2D fault geometries and models of fault networks.

Investigation of Lithospheric Structure in NE India Based on Love Wave Data

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We analyzed data of 228 earthquakes of 5≤Mw≤6.9 to calculate the Love wave group velocity tomography and investigate lithosphere structure of NE-India. These events of 2013-2015 were recorded by 27 seismic stations of Indian Meteorological Department and Incorporated Research Institutions of Seismology. Multiple Filtering Technique is used to estimate fundamental mode Love wave group velocity dispersion curves between 4 and 70s for 846 paths. Then, we constructed Love wave group velocity maps at different periods from 5 s to 60s through inversion over 1°×1° grid indicating group velocity variations between ~2-4.6 km/s in this part of the India-Eurasia collision zone. Tomographic maps show good correlations with surface features and at lower periods sensitive to the uppermost crust have high variation related to different local geological features like sedimentary basin, basement rocks, Precambrian and metamorphic rocks. Bengal-Basin and Indo-Burma Ranges have lower group velocities at period ≤16s and S-wave velocity compared to those located at Shillong plateau, Mikir Hill and Eastern Himalaya range. Low-velocity zone systematically shifts eastward towards the southern part of Indo-Burma Range for periods from 16 to 38s. Prominent increase in group velocity from 38s is observed along NE direction of Indian continent to Shillong Plateau, Mikir Hill and Assam syntaxis. It reflects the upward crustal buckling the Indian plate caused by it being in a vice-like grip between the Eastern Himalaya towards its north and the Indo-Burma Ranges towards its east. At periods >50s low-velocity is observed in Tibetan plateau due to the presences of thick crust and partial melting in the middle-to-lower crust. Inversion of group velocity to 3-D model of SH show significant difference of shear velocity of the crustal structure and reveal low-velocity zone in mid-to-lower crust beneath southern Tibet. Mostly the Love wave inversion result matches with previous observed Rayleigh wave inversion one and discrepancies in some sections highlight the existence of the radial anisotropy.

Qualitative and Quantitative Validation of Local Site Response and Spatial Attenuation From Numerically Simulated Ground Motions

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Significant advancements in the efficiency of numerical codes for large-scale seismic wave propagation in the last decade have created a vital place for simulated ground motions in Probabilistic Seismic Hazard Analysis (PSHA) to fulfill the gaps observed in earthquake catalogues, especially associated with large magnitude events with very long recurring periods. Since a rigorous validation of generated ground motions is crucial before they are disseminated to the public for the purpose of PSHA, this research features several schemes for the qualitative and quantitative validation of ground motion simulations carried out against recorded ground motions over local domains and against established Ground Motion Predication Equations (GMPEs) from the NGA-West2 project on a regional scale.

We simulate moderate-sized aftershocks of the 2007 Niigata-Chuetsu earthquake in SW4 to investigate the advantages and limitations of three subsurface models with the following assessment criteria—reproduction of site response at specific locations, spatial attenuation of ground motions on a regional scale and scattering of seismic waves throughout the computational space. The subsurface models represent increasing complexity and sophistication in modeling techniques that may be preferred for specific applications. The site of interest for this large-scale numerical experiment is Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) and recorded ground motions are pulled for validation from one of its well-characterized geotechnical downhole arrays, Service Hall Array (SHA) and three stations from K-NET in Japan. In conclusion, we underline the importance of each validation scheme in distinguishing the response from the three subsurface models and juxtapose the High-Performance Computing (HPC) requirements observed at Los Alamos National Laboratory (LANL) against the modeling accuracy to emphasize the application-based viability of each model.

Simulation of Mw 7 2016 Kumamoto Earthquake Mainshock Using Dynamic Rupture Modeling

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The mainshock of the M_w 7 magnitude 2016 Kumamoto earthquake occurred on April 16, 2016, at 01:25 (JST) in the Kyushu Island (Yoshida et al., 2017), on the Futagawa and Hinagu fault system. Near-fault ground motions generated by the earthquake were recorded with high accuracy by the NIED strong-motion network (K-NET and Kik-net), the Japan Meteorological Agency (JMA) and the local-government seismic-intensity network (Irikura et al., 2020).

In this study, we used dynamic rupture modeling (Pitarka et al., 2021) to investigate the earthquake rupture and simulate the recorded near-fault ground motions. Following the slip models of Yoshida et al. (2017) and Asano and Iwata (2021), we randomly generated 500 and 858 stress models with three strong motion generation areas (SMGAs) with elevated stress drop, located on the Futagawa and Hinagu fault zones. The 3D Japan integrated velocity structure model (JIVSM) (Koketsu et al., 2008, 2012) was used in modeling the elastic wave propagation. Then, a linear regression method was applied to the eight endpoints of four fault segments, to define the location of the 45 km long rupture plane. We simulated the ground motion at 26 strong-motion stations within 18 km from the assumed fault plane. We used the misfit of PGV and cross-correlation coefficient (CCC) between the recorded and synthetic strong-ground motions at each site among 1358 scenarios, to isolate the rupture model that best fit the waveforms at 26 sites. The synthetic waveforms compare very well with the recorded ones at 16 of 26 sites of scenario No. 0174. We performed additional simulations focused on testing the effect of the rake angle on the quality of synthetic ground motion. Rupture scenarios with rake angles between 20 and 30 degrees performed relatively better. Thus, we concluded that the rake angle of the mainshock was in this range, which means that the northwest plate sinks 20 to 30 degrees towards the northeast, which is consistent with the previous research results (e.g., Yoshida et al, 2017; Asano and Iwata, 2021).

Observations and Modeling of the 2021 Haiti Earthquake

Poster Session · Wednesday 20 April · Conveners: H. Zoe Yin, University of California, San Diego (hyin@ucsd.edu); Alice-Agnes Gabriel, Ludwig-Maximilians-University of Munich (alice.gabriel@web.de); Roby Douilly, University of California, Riverside (robyd@ucr.edu)

Landslides Triggered by the 14 August 2021, Magnitude 7.2 Nippes, Haiti, Earthquake

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The 14 August 2021, magnitude (M) 7.2 Nippes, Haiti, earthquake triggered thousands of landslides on the Tiburon Peninsula resulting in fatalities and damage to critical infrastructure. The Nippes, Haiti, earthquake was one of the deadliest natural disasters to occur in 2021, and the adverse effects of the earthquake-triggered landslides, especially those related to the intense sedimentation of waterways and landslide dams, will likely continue for months to years. Shortly after the event, we conducted a rapid response mapping effort using remotely sensed data and shared our observations daily with the U.S. Agency for International Development's (USAID) Disaster Assistance Response Team (DART) to assist with their situational awareness. Whereas these and other observations gathered after this event will likely help improve understanding of landslide susceptibility on the Tiburon peninsula and elsewhere, the event also provides an opportunity to evaluate current methods of compiling earthquake-triggered landslide observations in emergency response situations. Here, we discuss the emergency response effort and present an overview of the landslides triggered by the earthquake. We compare the characteristics of the 2021 landslides to those triggered by the M 7.1 earthquake that occurred near Port-au-Prince, Haiti, in 2010, which had a similar magnitude, similar mechanism and occurred along the same fault zone as the 2021 event. We discuss the continued impact that newly triggered landslides may have on the landscape for years to come, and discuss specific landslides observed that may pose a threat to people, property and/or infrastructure. This event highlights the lasting impact that cascading earthquake hazards can have on a landscape and provides an opportunity to assess and improve our current capacity for landslide mapping in response to emergency situations.

Limitations of a Teleseismic-only Dataset for 2021 mw7.2 Nippes, Haiti, Finite Fault Modeling: Improved Modeling Capability for Joint Teleseismic and Regional Inversion

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Since late 2007, the U.S. Geological Survey National Earthquake Information Center (NEIC) has routinely produced a teleseismic finite fault model (FFM) in the hours following a significant earthquake (generally Mw7+). In mid 2021, NEIC introduced updates to the FFM capabilities that allow joint inversion of regional strong-motion accelerometer and static and high-rate Global

Navigation Satellite System (GNSS) observations, in addition to broadband teleseismic data. The August 14, 2021 M_w7.2 Nippes, Haiti, earthquake prompted an effort to expand these new capabilities even further; this time to include Interferometric Synthetic Aperture (InSAR) data. The motivation to include InSAR was driven by the difficulty obtaining a reliable slip model for this event with other data sources. Interference from a M_w6.9 earthquake offshore Alaska that preceded the Haiti earthquake by about 31 minutes reduced the number of usable teleseismic waveforms. The intial teleseismic-only FFM preferred a bilateral rupture with maximum slip occurring directly east of the hypocenter. Over several hours following the earthquake, other geophysical evidence suggested strong westward directivity of rupture and the NEIC teleseismic model was revised, placing the modeled fault region west of the hypocenter to force a westward-propagating rupture. The addition of one strong-motion accelerometer and four static GNSS sites afforded by the regional networks results in a main slip asperity just west of the hypocenter. Finally, joint inversion of broadband teleseismic, regional strong-motion accelerometer and static GNSS, in addition to two InSAR scenes acquired within 3 days of the earthquake, clarifies the unilateral, westward propagation of rupture. The capability to jointly invert InSAR alongside other regional and teleseismic data enables an improved understanding of the kinematic rupture process of the Nippes, Haiti, earthquake and contributes to NEIC's ongoing effort to prepare for future crustal earthquakes.

Slip in the 14 August Haiti Earthquake Derived From InSAR and Pixel Offsets

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The 14th August Mw7.2 Nippes earthquake occurred along the EW striking Enriquillo Plantain Garden fault zone (EPGFZ) in Tiburon peninsula, Haiti. The primarily left-lateral strike-slip event killed over 2000 people and affected more than 650,000 people in the region. We use InSAR to constrain slip in this earthquake. Here we use ascending and descending track interferograms from Sentinel-1A and 1B and ALOS-2 to map the coseismic surface displacements associated with the earthquake and estimate coseismic and early postseismic slip. The fault dip is fixed to be consistent with the USGS moment tensor solutions for the main shock and aftershocks. We find oblique left-lateral slip on the primary EPFGZ with a peak of roughly 2 m. Oblique slip also occurs on the north-dipping thrust faults north of the EPGFZ. Peak slip occurs between 6-9 km depth on the EPGFZ at about the same locations as the USGS finite-fault solution. Using the staggered nature of the interferograms, we find a range of moments Mw 7.1-7.3 that fit the displacements through August 15 at the time of the descending track acquisition. We also use post-event SAR acquisitions from Sentinel-1 to constrain significant postseismic moment release in the time following the earthquake.

Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?

Oral Session · Thursday 21 April · 8:00 AM Pacific

Conveners: Tuna Onur, Onur Seemann Consulting, Inc. (tuna@onurseemann.com); Rengin Gok, Lawrence Livermore National Laboratory (gok1@llnl.gov); Kristin Morell, University of California, Santa Barbara (kmorell@geol.ucsb.edu); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov); Mark Petersen, U.S. Geological Survey (mpetersen@usgs.gov)

Seismic Source Characterization for Probabilistic and Scenario Seismic Hazard Analysis Beneath the Complex Tectonic Setting

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Japan is built on a complex tectonic setting to deal with subduction earthquakes including megathrust and intraslab earthquakes, inland and offshore crustal earthquakes and earthquakes called background or diffuse seismicity whose seismic sources are difficult to identify. National-level probabilistic seismic hazard maps have been available since 2005 and are frequently updated to include the latest findings on faults and seismicity. The 2011 Mw9.0 Tohoku earthquake had a significant impact on the source characterization for PSHA (e.g., Morikawa and Fujiwara, SRL, 2016). In addition to the probabilistic seismic hazard maps, scenario seismic hazard maps for over 100 faults have been released to assess ground motions for specific faults with return periods of more than 1000 years. Here, we would like to discuss four issues regarding source characterization in probabilistic and scenario seismic hazard analysis in the complex tectonic setting. Firstly, the declustering of the earthquake catalogs in PSHA after the 2011 Tohoku earthquake: the source region of the 2011 Tohoku earthquake and its seismic activity are more active than before the earthquake. Declustering in the post-2011 earthquake catalog is one of the major challenges in modeling the frequency of earthquakes. Secondly, Mmax modeling of background or diffuse seismicity. Aftershocks of the 2011 Tohoku earthquake exceeded the Mmax of specific faults in pre-2011 seismic hazards, then Mmax of background seismicity were revised M8.5 for plate-boundary, M7.3-8.4 for intraslab and M7.3-7.5 for crustal earthquakes. Thirdly, the search for the variability in source parameters to match the variability in ground motions. The number of source parameters is greater than a single "sigma" of the ground motion prediction equation, indicating broadband ground motion simulations require correlations among source parameters. Finally, lessons learned from the 2011 Tohoku megathrust and the 2016 Kumamoto crustal earthquakes show considerations for the treatment of extreme sources and ground motions with outliers.

Catalog Harmonization Using Reliable Mws

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Moment magnitude (Mw) is the preferred magnitude scale for the PSHA ready earthquake catalogs. For sparse local and regional seismic networks, an accurate estimate of Mw is important for establishing good quality of seismic catalog and estimating recurrence of earthquakes for seismic sources. The Gutenberg-Richter a- and b-values can vary significantly biasing the recurrence rates (higher or lower). This is usually caused by the magnitude conversions from small events of traditional magnitudes (M_L, mb and Ms) that are not accurately derived. If the moment magnitude (Mw) value is greater than 5.0, it is usually well-determined by global moment tensor solution centers (e.g. GCMT, ETHZ). However, reliable moment magnitude estimates for small/moderate size events (5.0>Mw>3.5) can be difficult to obtain due to the uneven distribution of stations, the complex tectonic structure and effects of strong structural variations that are not necessarily well-captured with a simple 1-D velocity and attenuation structure.

We use the coda calibration technique to directly obtain Mw from source spectra using the Java-based Coda Calibration Tool (CCT) (https://github.com/LLNL/coda-calibration-tool). The method is based on empirically derived coda envelope shape and path (attenuation and geometrical spreading) parameters. We applied this technique for PSHA studies in the Middle East, the Caucasus and Central Asia. In Central Asia, after directly obtaining Mw for as many events as possible, there still remained many events in the catalog for which a conversion was needed from other magnitude scales such as ML, mb, Ms or the Soviet-era scales such as K class, MLH and MPV. Majority of these events had K class available along with other magnitudes. Fortunately, a few stations from the former Soviet Union were co-located with modern broad-band sensors. This provided an opportunity to directly compare moment magnitudes (Mw) with Soviet type magnitudes (especially K class, since it was available for majority of the events in the catalog), and to derive region-specific relationships between them.

Coda Envelope Moment Magnitudes and the Re-evaluation of Magnitude Conversion Relations for Seismic Hazard Assessment in Southeastern Canada

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Although moment magnitude (M_W) is the preferred magnitude for hazard assessment, M_W for many Canadian earthquakes is derived from conversion relations. Previous research found that a time-dependent difference of about 0.1 magnitude units in the M_N-M_W conversion, where M_N is the Nuttli magnitude, resulted in a 15% difference in hazard for the Western Quebec Seismic Zone. The difference between pre- and post-1995 events was traced to a change in frequencies at which M_N was calculated. For over a decade, M_W has been calculated via regional moment tensor inversion for moderate to large earthquakes in eastern Canada but it is difficult to calculate M_W for events below M_W 3.5. Recently, the coda envelope moment magnitude method has been used to calculate moment magnitude (M_{WC}) for earthquakes in the active seismic zones of southeastern Canada since the mid-1990s for M_W as low as 1.5, below the threshold used in hazard assessment (~M_W 2.5). As a result, magnitudes for fewer events will require conversion for hazard assessment and the large suite of M_{WC} measurements allows for the re-evaluation of the M_N-M_W conversion with a much larger data set than was used for the current conversion relation. A comparison of M_{WC} to converted M_W values shows that the conversion relation still appears valid for the larger events but does not provide a good fit to the smaller ones. A re-evaluation of the relation is underway. There is some suggestion that different conversions should be used for different tectonic provinces (e.g. Shield vs. Appalachians). Seismic hazard in eastern Canada is based largely on past seismicity. The largest earthquakes are the ones of most concern for hazard but the smaller ones control the shape of the magnitude recurrence curve and a change in their population could affect the hazard values for some regions. An increase in the value of M_W for small earthquakes would increase the b-value and thereby decrease the rate of the largest earthquakes.

A Systematic Examination of the Effects on the Seismic Hazard of Non-uniqueness in Declustering an Earthquake Catalog

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There is no unique solution to the problem of declustering a seismicity catalog. Zaliapin and Ben Zion (2020) present a method for removing nearest neighbor earthquakes from a complete catalog. The number of events in the residual catalog depends on a continuous parameter, α_0, called the "cluster threshold". For a range of values of α_0, the temporal distribution of events in the residual catalog approaches a Poissonian distribution, suggesting that the family of residual catalogs in this range has been declustered. For intuitive simplicity, we define $f_R=f_R(\alpha_0)$ to be the fraction of earthquakes remaining in the residual catalog.

We study the probabilistic seismic hazard associated with this family of declustered catalogs on a series of east-west profiles across California. For each point on a profile we calculate a series of hazard curves: 1) the hazard from the USGS declustered catalog C3 used to develop the 2018 National Seismic Hazard Map, 2) the hazard from a series of catalogs for a range of values of f_R from 0.1 to 0.9 and 3) the hazard from the median UCERF3 estimate of fault hazards. For this exercise, we use simplifications in hazard calculations, as we consider only an adaptive smoothing algorithm to obtain the background seismicity from the declustered catalogs and use only one ground motion prediction equation. In spite of these simplifications, the total hazard estimated for our profiles, represented by the ground motion with probability of exceedance of 2% in 50 years, is generally a reasonable approximation to the complete 2018 NSHM model. The hazard generally increases as f_R increases, with $f_R \approx 0.4$ roughly reproducing the hazard from the C3 catalog. A surprising result is that the increase at some places is neither linear nor monotonic because of the behavior of the adaptive smoothing algorithm. Also, the value of f_R that most nearly approximates the hazard from the C3 catalog is spatially variable.

Linear Combination of GMMs Using Optimized Weights Based on Record-free Covariance

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Linear combination of prediction models is often used to reduce epistemic uncertainties. In the probabilistic seismic hazard analysis (PSHA), for example, multiple prediction models of ground motions (GMM) are combined using the logic tree approach. The optimized weights, minimizing the standard deviation of residuals for the combined model, can be determined if a covariance matrix among models is available (Kwak et al., 2018), and the covariance of residuals can be calculated if records are available. The limitation in this approach is that ground motion records are needed for the covariance matrix calculation. For some GMMs the IMs from records are available (e.g., NGA West2 flatfile), but for most of GMMs, IMs from records are limited to access so that only median prediction and standard deviation of residuals can be obtained. For the latter case the weights were often suggested based on the inverse of the standard deviation.

This study suggests a way to find the covariance matrix of GMM residuals without IMs from records and eventually the optimized weights. Using the difference of median predictions between two GMMs and their standard deviations the covariance can be calculated. The process includes 1) randomly generate earthquake scenarios (i.e., magnitude, source-to-site distance, site condition); 2) apply the scenario to each GMM; 3) find the difference of median predictions and 4) calculate the covariance using the difference and the pre-defined standard deviation of residuals for each GMM. The variable in this approach is that the covariance changes based on the distribution of earthquake scenarios, but the variation of optimized weights due to the different distributions is not significant. The optimized weights determined from the records-free covariance matrix successfully reduce the uncertainty of the combined model.

Ground Motion Models: Which Way Henceforth?

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Ground motion models (GMMs) prescribe the distribution of ground motions that is associated with event occurrence within the framework of probabilistic seismic hazard analysis (PSHA). I overview recent trends that impact the three attributes of GMMs that drive PSHA results and discuss the interactions between these attributes. The attributes are: (i) the median model (*i.e.* median amplitudes of response spectral ordinates and peak ground motions as functions of magnitude, distance and site parameters); (ii) epistemic uncertainty (*i.e.* alternative models that reflect lack of knowledge in the correct median); and (iii) aleatory variability (*i.e.* random scatter about the median). I focus on two recent general trends. The first stems from advancements in PSHA approaches for site-specific applications; the median, epistemic and aleatory models can all be refined by using site-specific ground motion recordings to improve upon generic regional models. These improvements can increase the reliability of the median and better define its epistemic and aleatory uncertainties. Moreover, the reduction in aleatory variability that results from site-specific treatment of site response can significantly reduce the computed PSHA result—thus justifying the expense of the recording program for critical sites. Second, I consider how epistemic and aleatory uncertainty are inherently intertwined if modeling epistemic uncertainty using a backbone approach (*i.e.* a central model with alternative branches expressing uncertainty in the median). The distribution of ground motions input to the PSHA should be considered in its totality (*i.e.* weighted sum of the branches and the distribution about each) to avoid double counting uncertainty.

Ground Motion Simulations in Azerbaijan: Application to PSHA

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One of the main steps in the probabilistic seismic hazard assessment (PSHA) is ground motion characterization using regional ground motion models (GMMs). In this study we relied on physics-based broad-band ground motion simulations for earthquakes in Azerbaijan to determine appropriate period-dependent weights for GMMs that represent different tectonic regimes in order to incorporate wave path effects that are specific to the region. Azerbaijan is an unusual case in that the wave propagation differs greatly between the Caucasus mountain ranges and the Kura Basin where thick sediments are present. We used a hybrid ground motion modeling technique that combines a deterministic approach to model the low frequency part of ground motion (< 1 Hz) and stochastic approach to model high frequencies (up to 10Hz). We computed ground motion for Mw6.5, Mw7, and Mw7.5 scenario earthquakes in three tectonically different areas of the country, including Absheron, located near the capital Baku, Shamakhi and Ganja. The synthetic ground motion data base, comprising accelerograms computed on a dense grid of stations was finally used to constrain and determine weights to derive region specific GMMs. The proposed GMMs and their weighting factors derived from comparisons with those developed for regions with different tectonic regimes, including NGA West2 and NGA East GMMs were later used in PSHA for Azerbaijan and surrounding regions.

PSHA Consistently Overpredicts Historically Observed Shaking Data

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According to recent studies, probabilistic seismic hazard assessments (PSHA) based on current practice consistently overpredict historically observed shaking data, although both the forecasts and datasets are compiled by different groups. Results from California, Japan, Italy, Nepal and France show a similar trend when comparing predicted and observed fractional exceedances, even correcting for the lengths of the observation times. This overprediction is intriguing because numerical studies (Vanneste et al., 2018) show that for PSHA analyses that correctly model the seismicity and ground motion, the observed fractional exceedance is equally likely to be above or below that predicted. That study also showed that the standard deviation of fractional exceedances should decrease for larger ratios of observation time to return period length i.e., observations should be closer to the prediction as observation time increases. However, in nearly all regions studied to date the observations are below the predictions and no consistent improvement appears with longer observation times. The consistent overpredictions across a variety of tectonic settings suggest possible systematic biases in either the historical observations, the source models or the ground motion models used in the PSHA, or all three. Investigating the causes of this discrepancy has the potential to improve seismic hazard assessments.

New Approach for Modeling 3D Path Effects From Cybershake Simulations in Non-ergodic Ground-motion Models

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The results of 3-D simulations, such as Cybershake for the LA region, show significant effects of the 3-D crustal structure on the ground motion at a specific site from a particular source location. In traditional ergodic ground-motion models (GMMs), such as the NGA-W2 GMMs, these systematic effects are effects are treated as aleatory variability that apply to all source/site pairs. Recently, non-ergodic GMMs have been developed in which the computed ground motion depends on the site and source location and not just on the magnitude and distance. The current approaches for non-ergodic GMMs include the site/source-specific path effects through an isotropic source-specific geometrical spreading term (Landwehr et al, 2016) and through cell-specific linear-distance scaling that mimics the effects of a 2-D Q structure. Neither of these approaches capture the path effects due to the 3-D velocity structure that is seen in the 3-D simulations. To include 3-D path effects in the GMM, we compute the residuals for the 3-D numerical simulations of the Cyber-Shake relative to a simplified GMM and use the resulting within-site residual to estimate the spatial distribution of the non-ergodic path terms through the varying coefficient model (VCM)using a two-step approach. The first step estimates the non-ergodic path terms for each site separately. The second step estimates the non-ergodic path terms for each source separately. The VCM method leads to spatially smooth non-ergodic path terms that can be extrapolated to sites without simulation results.

For T=3 sec PSA, the non-ergodic path terms range from -1.0 to 1.0 ln units, corresponding to factors of 0.4 to 2.7 in the median ground motion compared to the ergodic approach. With the non-ergodic path terms, the within-site single-path aleatory variability for the 3-D simulations is reduced to 0.36 (ln unit), which is similar to the empirical result of Lin et al. (2011) for Taiwan. We show an example of hazard for T=3 sec computed using ergodic and non-ergodic GMMs based on the 3-D simulations.

Non-ergodic PSHA Using Fully-deterministic Physics-based Models for Southern California

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The CyberShake platform, developed by the Southern California Earthquake Center, performs physics-based probabilistic seismic hazard analysis using 3D wave propagation simulations with reciprocity. One of the key inputs to CyberShake is the earthquake rupture forecast (ERF). Previous regional CyberShake studies have used an ERF derived from UCERF2, extended with a kinematic rupture generator. Here we investigate the impact of using a fully physics-based ERF created with the Rate-State Earthquake Simulator (RSQSim) software. We used RSQSim to generate a 715,000-year rupture catalog for the UCERF3 fault system that includes full slip-time histories along fault planes.

Building on the work in Milner et al. (2021), we performed CyberShake Study 21.12 using the RSQSim ERF to calculate the first regional probabilistic hazard map with fully-deterministic models. We computed approximately 26 million two-component seismograms and long-period (T≥2 sec) CyberShake-RSQSim hazard curves for 335 sites in the Southern California region. We will present results from this study, including comparisons with empirical ergodic ground motion models (GMMs) and with CyberShake Study 15.4, which used the UCERF2 ERF in the same region. When aggregated across all sites and sources, we find that the distribution of ground motions generated in Study 21.12 closely matches the distribution from ergodic GMMs. Additionally, hazard maps computed in Study 21.12 are qualitatively similar though show slightly lower than those from Study 15.4 at longer periods, with increased differences at shorter periods. This study demonstrates a practical approach for performing fully physics-based PSHA and provides an opportunity for detailed investigations of non-ergodicity in ground motions.

PSHA Input Considerations in Central Asia

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A new probabilistic seismic hazard assessment (PSHA) is being undertaken for Tajikistan, Kyrgyzstan and Kazakhstan by local agencies with the support of the Lawrence Livermore National Laboratory. The study includes a major bulletin unification effort that collects and digitizes all paper-based seismic bulletins in the countries' archives as well as compiling all available digital data. The resulting database of about 26 million arrivals along with the existing data from the International Seismological Centre (ISC) was used to recalculate magnitudes and relocate earthquakes. About 72,000 events from non-tectonic sources were identified by local agencies and these events were removed from the earthquake catalogue. After general clean up and removal of events from non-tectonic sources, the earthquake catalogue contained about 450,000 events. Most of the digital era data was substantially improved by new magnitude calculations and earthquake relocations. However some issues related to low resolution magnitude and location determinations (mainly from the analogue era) remained. This presentation describes some of these issues related to the quality of the PSHA inputs in Central Asia.

'We're Gonna Need a Bigger Boat': Wrestling a Large Seismic Hazard Model for Seismic Risk Assessment in Canada

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Creating robust but computationally tractable probabilistic seismic hazard and risk models for a large and tectonically diverse country like Canada poses a significant challenge. At its core, the upcoming national seismic risk model for Canada uses the 6th Generation Seismic Hazard Model (CanSHM6).

CanSHM6 itself is computationally intensive due to a multitude of factors such as: multiple characterizations of five tectonic regimes, 32 ground motion models (GMMs), multiple source and magnitude-frequency characterizations and the size of the country combined with a large hazard integration distance. This results in upwards of 105 logic tree branches with millions of possible ruptures in certain parts of the country. Running seismic risk calculations involves calculating the shaking impact of each of the ruptures on exposed assets in Canada, given their vulnerability to damage and loss. For 5 possible damage states at 2.2 million unique combinations of building typologies and locations across the country, each with their own site condition, represented by Vs30, the calculation of nationwide risk from the full hazard logic tree becomes impossible even on machines with high processing power. This work describes efforts undertaken to simplify and adapt CanSHM6 for national seismic risk calculations. Specifically, we outline work to quantify the impact of using smaller portions of the seismic hazard logic tree, through sensitivity testing and strategies employed to break the hazard and risk calculations into sufficiently small portions that can be aggregated during post-processing. As future hazard models seek to optimize efficiency, precision and accuracy, considering all known sources of uncertainty, the impacts to downstream models, like seismic risk calculations, need to be considered. This will be of particular importance as more countries move to a risk-based design.

Probabilistic Seismic Hazard Assessment in Lebanon

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The present work focuses on Lebanon, a country with a high seismic potential since it is located along the Levant fault system, a ~1200 km long strike-slip fault that accommodates the northward motion of the Arabian plate relative to the Sinai-Levantine plate (with a slip rate around ~5 mm / year, Le Béon et al. 2008). Our aim is to determine probabilistic seismic hazard for the country. In this area, the observation datasets available both to model earthquake recurrence and to select ground-motion models are scarce. The instrumental catalog is typical of a low-seismicity region, and is not representative of the large destructive earthquakes that occurred in the past. We develop a set of smoothed seismicity models based on instrumental data to forecast off-fault seismicity, combined with a set of moment-balanced fault models that account for best-characterized faults. Both the Gutenberg-Richter model and the characteristic model are considered for forecasting earthquakes on the faults, with earthquake frequencies inferred from geological slip rates on faults. We show that for most sites in Lebanon, the hazard at 475 years return period is controlled by the faults with a negligible contribution from the background seismicity. We set up a logic tree to account for uncertainties on the choice of the recurrence model for faults, on the maximum magnitude, on slip rate estimates as well as on maximum fault depth. In the case of Beirut city, located on the hanging-wall of the Mount Lebanon fault, the PGA at 475 years varies between 0.2 and 0.45g (16th and 84th percentiles). The exploration of the logic tree demonstrates that the choice of the recurrence model governs the overall variability on hazard estimates. The next step will be to relax segmentation on faults and account for fault section connectivity.

Earthquake Recurrence Model for the Colombia–Ecuador Subduction Zone Constrained From Seismic and Geodetic Data, Implication for PSHA

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Probabilistic seismic hazard assessment relies on long-term earthquake forecasts and ground-motion models. Our aim is to improve earthquake forecasts by including information derived from geodetic measurements, with an application to the Colombia–Ecuador megathrust. The annual rate of moment deficit accumulation at the interface is quantified from geodetically based interseismic coupling models. We look for Gutenberg–Richter recurrence models that match both past seismicity rates and the geodetic moment deficit rate, by adjusting the maximum magnitude. We explore the uncertainties on the seismic rates (a- and b-values, shape close to Mmax) and on the geodetic moment deficit rate to be released seismically. A distribution for the maximum magnitude Mmax bounding a series of earthquake recurrence models is obtained for the Colombia–Ecuador megathrust. Models associated with Mmax values compatible with the extension of the interface segment are selected. We show that the uncertainties mostly influencing the moment-balanced recurrence model are the fraction of geodetic moment released through aseismic processes and the form of the Gutenberg–Richter model close to Mmax. We combine the computed moment-balanced recurrence models with a ground-motion model, to obtain a series of uniform hazard spectra representative of uncertainties at one site on the coast. Considering the recent availability of a massive quantity of geodetic data, our approach could be used in other well-instrumented regions of the world.

A Strategy to Build a Unified Dataset of Moment Magnitude Estimates for Low-to-moderate Seismicity Regions Based on European-Mediterranean Data: Application to Metropolitan France

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The moment magnitude (Mw) scale is largely used in seismic hazard assessment to characterize earthquake events both in the earthquake catalogues and in the ground motion databases. Several Mw values can be published by different authors for the same event due to the use of different computation methods, input data, or seismic networks. In this study, we developed a novel strategy to assign a unique and unified Mw value to each event. This hybrid strategy is based on (i) ranking Mw sources in five levels from global to specific studies, (ii) inter-comparisons of Mw estimates at the European-Mediterranean scale with a reference dataset, consisting of Mw values given by the global and European centroid moment tensor services and (iii) using a Mw value threshold that are useful for low-to moderate seismicity regions such as metropolitan France, the target region of our study. For the European-Mediterranean region, we collected from 34 sources (bulletins, publications, …) 6752 Mw estimates of 4454 shallow events that occurred between 1963 and 2019. A unified Mw value could be attributed to 3351 events and to 185 events in the case of the France region. Comparison of this new unified Mw dataset shows good agreement with the Italian CPTI15 catalogue over the 4.0<Mw<7.1 range whereas a systematically larger value is found compared to the Mw values published in French datasets (SI-Hex, RESIF-RAP) covering the 3.0<Mw<5.0 range.

Earthquake Probabilities Using the Long-term Fault Memory Model

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Earthquake hazard mitigation often relies upon forecasts giving the probability of a large earthquake occurring in a region over a specific timeframe. These forecasts assume that a probability distribution describes the inter-event times between large earthquakes and then use this distribution to calculate earthquake probabilities. However, common statistical distribution models (lognormal, Weibull, etc.) ignore the complexities of the strain accumulation and release processes that drive earthquakes. They assume that a large earthquake releases all accumulated strain, a simplification that conflicts with earthquake histories showing complex temporal patterns. These common statistical models also allow earthquake probability to decrease as time since the previous event increases and additional strain accumulates. Here we use the recent Long-Term Fault Memory (LTFM) model, which better reflects the underlying strain accumulation and release processes, to calculate earthquake probabilities along the southern San Andreas fault. The LTFM model produces similar 30-year forecasts to the other models today, but by 2100 the LTFM forecast is 38% higher. Because LTFM does not assume that strain resets after each earthquake, LTFM can incorporate the specific timing of past earthquakes, yielding more realistic forecasts than current models, which by design cannot meaningfully incorporate this information.

Comparison of Natural and Mining-induced Seismicity Hazard: A Case Study for Sudbury, Ontario

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A probabilistic seismic hazard assessment is conducted for a site in Sudbury, Ontario which is known for mining activities and related industries. The assessment is based on a Monte-Carlo simulation approach. The 6th generation seismic source model of Canada (Kolaj et al., 2020) is adopted as the base regional model and is refined to better capture contributions from local seismogenic sources. To this end, a unified earthquake catalog is compiled and available tectonic, geologic and paleoseismic information is reviewed. The sources of natural and mining-induced seismicity are characterized accordingly. A suite of ground-motion models is developed based on the scaled backbone approach (Atkinson et al., 2014). The NGA-East seed models and an alternative model proposed by Atkinson et al. (2015) for earthquakes in Southern Ontario are considered for this purpose. The selected site is located at the margin of regional sources. The sensitivity of hazard estimates to the interpreted boundaries of source zones and alternative spatial distributions of events are quantified. A hazard fractile analysis is performed. Seismic hazard levels for median, mean and different percentiles are computed for return periods from 200 years to 10,000 years. Hazard levels and contributions from natural and mining-induced seismicity sources are compared.

A Regionally Adaptable Ground-motion Model for Fourier Amplitude Spectra of Shallow Crustal Earthquakes in Europe

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Typical seismic ground-motion models predict the response spectral ordinates (GMM-SA), which are the damped responses of a suite of single-degree-of-freedom oscillators. Response spectra represent the response of an idealized structure to input ground-motion, but not the physics of the actual ground-motion. To complement the regionally adaptable GMM-SA of Kotha et al. (2020), we introduce a model capable of predicting Fourier amplitudes (GMM-FA), developed from the Engineering Strong Motion (ESM) dataset for pan-Europe. This GMM-FA reveals the very high variability of high frequency ground-motions, which are completely masked in a GMM-SA. By maintaining the development strategies of GMM-FA identical to that of the GMM-SA, we are able to evaluate the physical meaning of the spatial variability of anelastic attenuation and source characteristics. We find that a fully data-driven geospatial index, Activity Index (AIx), correlates well with the spatial variability of these physical effects. AIx is a fuzzy combination of seismicity and crustal parameters and can be used to adapt the attenuation and source non-ergodicity of the GMM-FA to regions and tectonic localities sparsely sampled in ESM. While AIx, and a few other parameters we touch upon, may help understand the spatial variability of high frequency attenuation and source effects, the high frequency site-response variability–dominating the overall aleatory variance–is yet unresolvable. With the rapid increase in quantity and quality of ground-motion datasets, our work demonstrates the need to upgrade regionalization techniques, site-characterisation and a paradigm shift towards Fourier ground-motion models to complement the traditional response spectra prediction models.

High-pass Corner Frequency Selection for Implementation in the USGS Automated Ground Motion Processing Tool

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The Next Generation Attenuation projects require the processing of raw ground motion records to reduce noise artifacts. NGA procedures for ground motion processing require human inspection to select high-pass corner frequencies (fcHP) by considering the signal-to-noise ratio (SNR), the shape of the Fourier Amplitude Spectra and potentially unphysical features such as wobble in the displacement trace (e.g., Goulet et al., 2021). This process is time-intensive, which motivates using automated codes to streamline the processing. The United States Geological Survey (USGS) developed an automated processing code (gmprocess; Hearne et al. 2019) which, by default, selects the fcHP based on SNR.

We extend gmprocess to add displacement checks, with the aim of reducing displacement wobble and generating more reliable long-period response spectra (PSA). Two displacement criteria are considered: (1) limits on the maximum absolute displacement at the end of the time series (Dawood et al. 2016) and (2) a limit of the amplitude of a polynomial with a configurable order fit to the displacement trace. The limiting amplitude is in the form of a configurable ratio of the maximum displacement. We assess the performance of the different procedures using recordings from the 2020 M5.1 Sparta, North Carolina and the 2013 M4.7 Southern Ontario earthquakes. With the SNR-only criteria, 13% of signals have displacement drift that is absent in manually processed records. Among those records with drift, about half have PSA differences in excess of 5% for oscillator periods ≤ 10 sec. The end of record displacement criterion is not able to consistently improve on the SNR-only approach, whereas the polynomial fit method (applied with an order of 6 and displacement ratio of 0.02) performs well. The gmprocess code now includes these as optional criteria for processing ground motion data. These automated procedures are not suitable for cases with displacement offset from fling step or ground failure.

Developing an Empirical Relationship Between Different Distances Metrics for Seismic Hazard Assessment

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The seismic hazard of an area is determined based on the ground motion observed at that site. The intensity of the ground motion can be predicted using Ground motion models (GMMs). These equations are generally developed based on the rupture model, which uses distances such as Joyner-Boore distance (RJB) and Rupture distance (RRUP). However, Probabilistic Seismic Hazard Analysis (PSHA) utilizes point-source based distances like Epicentral distance (REPI) and Hypo-central distance (RHYP), where the fault geometry may not be known. To obtain an accurate seismic hazard of an area, we need to determine the relationship between the distance metrics from these two different models. In this study, we develop empirical relationships between various distances to convert from one distance to another. This avoids conducting computationally intensive tasks such as computing finite-fault-based distances for different fault geometry of a virtual rupture plane for each point source and vice versa. The empirical equations provide the relation between two distance metrics (RJB and RHYP, RRUP and REPI, etc.) based on the magnitude of the earthquake and the dip angle of the fault. We also discuss methods to include the variability due to the conversion of the distance metrics in the PSHA. We have compared the results with previous equations developed by various researchers and found a good fit. The equations developed in this paper can be directly applied in PSHA and is independent of the GMMs used for seismic hazard calculations. Furthermore, the equations developed in this study can also be used for different fault geometries with a range of dip angles varying from 10° to 90°, different magnitude earthquake events ranging from 4.0 to 8.0 and a distance upto 1000 km.

Rethinking PSHA: Are We Using Appropriate Inputs for the End Goal?

Poster Session · Thursday 21 April · Conveners: Tuna Onur, Onur Seemann Consulting, Inc. (tuna@onurseemann.com); Rengin Gok, Lawrence Livermore National Laboratory (gok1@llnl.gov); Kristin Morell, University of California, Santa Barbara (kmorell@geol.ucsb.edu); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov); Mark Petersen, U.S. Geological Survey (mpetersen@usgs.gov)

A First Look at the Revised Seismic Hazard in Southwest Iceland From Synthetic Finite-fault Earthquake Catalogs Predicted by a New Physics-based Bookshelf Fault System Model

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Throughout history, damaging earthquakes have repeatedly struck in Southwest Iceland, the country's most populated and seismically active region. There, the interplate earthquakes do not occur on sinistral strike-slip faults parallel to the plate margin, but instead on a dense array of near-vertical dextral faults striking perpendicular to the plate margin. This "bookshelf" faulting has not explicitly been accounted for in probabilistic seismic hazard assessment (PSHA). Instead, incomplete earthquake catalogs and simplistic seismic sources have been used. A physics-based PSHA that accounts for the complex finite-fault rupture would provide a much more realistic and reliable way to evaluate the seismic hazard. In this study, therefore we take the first step and expand the conventional PSHA by simulating multiple finite-fault earthquake catalogs for the entire bookshelf system based on a new, physics-based 3D fault system model of Southwest Iceland that explains the observed Icelandic earthquake catalogs. The systematic spatial variation of fault slip-rates is modeled by discrete subzonation of the fault system and the equivalent parameters of seismic activity (Mmax , a- and b-values) estimated. Thus, the Monte Carlo simulated finite-fault earthquake catalogs are both compatible with the earthquake faulting and the long-term seismicity in the region. The ground motion amplitudes from each synthetic earthquake are predicted at a grid of hypothetical sites using new Bayesian ground motion models for Iceland. Thus, this first look at the revision of PSHA for Southwest Iceland completely avoids the use of limited statistics from observed catalogs and has firm roots in a completely physical finite-fault system of the bookshelf transform zone. The results of this study will be compared to latest PSHA-efforts (i.e., ESHM20) and those of a parallel study using the same physics-based fault system but kinematic earthquake rupture modeling in the CyberShake framework.

Composite ShakeMaps for Earthquake Sequences and for Testing and Observed Probabilistic Seismic Hazard Analyses

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Traditional Probabilistic Seismic Hazard Analyses (PSHA) provide estimates of the likelihood of shaking exceedance over a period in the future. Observed ground motions from historical earthquakes are not explicitly included in such calculations. Rather, they are derived from event catalogues from which ground motions are estimated and scaled by their likelihoods. As an alternative, we recreate observed ground motion exceedances from actual events and the best representation of their observed shaking for selected past time periods. Using USGS ComCat as our catalog, we use ShakeMap to map the maximum observed shaking for select space-time windows. This type of seismic hazard map naturally contains site amplification, and—unlike PSHA—they are not declustered, so aftershock shaking is included. Any direct PSHA comparison to our observed seismic hazard analysis (OSHA) must consider declustering and requires amplification of PSHA from rock to soil. In addition to peak shaking, we can provide observed, location-specific hazard curves, including how many events exceeded any specified shaking level. With the tools developed, we can now generate OSHA for the globe (using the ShakeMap Atlas), regionally, or for all ShakeMaps in a specified space-time window. For example, we can map the maximum shaking and the number of exceedances for any intensity metric for any given mainshock-aftershock sequence. For California, we've supplemented historical ground motion and intensity data with the California Historical Intensity Mapping Project dataset for better coverage of observed intensities. For visualization, we present our map-based and site-specific hazard curves using Tableau, which facilitates a user-friendly, web-based presentation. The beauty of OSHA is that we can now answer straightforward questions like, "How often was shaking felt in Pasadena over the past decade?" or "How many times was a particular bridge shaken above 0.2g during the Landers-Big Bear earthquake sequence?"

Evaluating Ground Motions From Deep Earthquakes in Malawi

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The current seismic hazard assessments for Malawi use ground motion models (GMMs) developed from global datasets. Considering Malawi's unique geological setting along the East African Rift System (EARS) and its unusually deep seismogenic zone, it is unclear whether these models can predict the expected ground motion levels accurately. Several faults with the potential to host magnitude (M) 7-8 earthquakes were recently identified during an update of the region's active fault database, highlighting the vulnerability of the surrounding communities. We explore the available ground motion records from earthquakes along the eastern and western branches of EARS to evaluate the suitability of the global GMMs commonly used, with particular focus on Malawi events, focal depths of the earthquakes and ground motions at close distances. First, we compile a regional catalogue of earthquakes with publicly available waveform data using global and local catalogues. We find 805 events (M 3 to 6) since 1980 with available waveforms from stations within 300 km. Data are scarce for events larger than M 5, especially at distances less than 100 km. Furthermore, the event locations were generally determined using stations at large distances (>400 km). Thus, we use NonLinLoc to relocate and improve the locations and depths of 287 events, finding focal depths down to 40 km. Ground motions are generally overestimated at close distances (<100 km) by the global GMMs, especially at longer oscillator periods and peak ground velocity. Finally, we assess whether a regional GMM adapted from the global GMMs with an additional depth parameter is needed to better describe Malawi's ground motions. This work can be used in future seismic hazard assessments for the region to better quantify the expected ground motion levels.

Homogeneization of the Moment Magnitude Estimates Available in the French Datasets and Implications on Ground Motion Model Variability

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Probabilistic seismic hazard assessment requires earthquake events characterized in terms of the moment magnitude (M_W) scale both in the earthquake catalogues and in the ground-motion databases. These magnitudes can be either estimated directly after an inversion of the moment tensor or can be deduced from other magnitude scales using a scale conversion formula. However, for the same event, even its moment tensor based M_W estimates provided by different agencies may differ due to differences in computation methods, inverted data or seismic networks—especially among small-moderate sized events. A few recent studies have shown that erroneous M_W estimates may bias the magnitude-scaling of ground-motion in GMMs and that merging of inhomogenous M_W estimates leads to a larger 'apparent' between-event variability of the Ground-Motion Models [GMMs].

Various strategies have been adopted in the literature to define a unique, reference M_W for each event in earthquake catalogues and ground-motion databases. Some strategies follow a priority scheme to prefer an M_W source over another, e.g. the European-Mediterranean Earthquake Catalogue. While others prefer to correct the M_W estimates of each source for their systematic deviation relative to an M_W reference source and then average the available M_W estimates for each event, e.g. the Italian Catalogue. In this study, we first attempt such homogenisation of M_W in the French RESIF-RAP dataset and then assess its impact on GMMs' between-event variability. Since in low-moderate seismicity regions of Europe, small-moderate sized events significantly contribute to hazard estimates, it becomes critical that their M_W estimates are homogenised prior to development of regional seismic source models and GMMs. We present the progress towards such homogenisation of M_W in the French context.

Precariously Balanced Rock Validation of Earthquake Ground-motion Models in Southern California

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Estimates of future earthquake ground shaking employ ground-motion models (GMMs) derived from limited instrumental recordings of historical earthquakes. However, a critical issue is that there is no method to empirically validate the resultant ground-motion estimates of these GMMs at the timescale of rare, large earthquakes. This lack of validation permits large uncertainty in the estimates of future ground motions, which is a major issue worldwide from disaster preparation to the safety of critical infrastructure. We address this issue and validate ground-motion estimates for southern California utilizing the unexceeded ground motions recorded by 20 precariously balanced rocks (PBRs). We modeled the age at which the fragile geometry of the PBRs formed with cosmogenic ^{10}Be exposure dating from ~1 to ~50 ka and also the probability of the PBRs toppling at different ground-motion levels. With these PBR data, we then validated the ground motions estimated for the site of each PBR. We used the "true mean" Third Uniform California Earthquake Rupture Forecast (UCERF3) seismic source model and the suite of Next Generation Attenuation Relationships for Western US (NGA-West2) GMMs using the OpenQuake engine. Each NGA-West2 GMM was validated individually to test their relative performance. We found that no NGA-West2 GMM estimated levels of earthquake ground shaking consistent with the observed survival of all 20 PBRs. The GMM I14 was identified as the worst performing and the ground-motion levels estimated by its upper branch were inconsistent with all 20 PBRs. At a 2475 year mean return period, the removal of this identified model resulted in a 2-7% reduction in mean ground-motion estimates at the PBR sites and the range of estimated 5th–95th fractile ground motions is reduced by 10-36%. Our findings show the value of validating ground-motion estimates against independent data, to eliminate the inconsistent GMMs and, in turn, reduce the uncertainties in the hazard estimates.

Searching for Fault Creep Over a Range of Timescales

Poster Session · Wednesday 20 April · Conveners: Alexandra E. Hatem, U.S. Geological Survey (ahatem@usgs.gov); Veronica Prush, McGill University (vbprush@ucdavis.edu); Christie Rowe, McGill University (christie.rowe@mcgill.ca); Chelsea Scott, Arizona State University (cpscott1@asu.edu)

A Comprehensive Catalog of Repeating Earthquakes for Northern California: Implications for Fault Creep, Slip Rates, Slip Partitioning and Transient Stress

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Repeating earthquakes, earthquakes that rupture the same fault patch more than once, are playing an important role in the study of source processes and fault behavior and have the potential to improve hazard assessment and earthquake forecast. They are believed to represent brittle failure of a stuck patch (asperity) on an otherwise creeping fault, and as such may offer insight into slip behavior at depth. We present a new catalog of repeating earthquakes for northern California developed by a systematic analysis of the entire NCSN waveform archive between 1984 and 2014 to identify earthquakes that are co-located, are of similar size and share similar waveforms. We find 27,675 events in 7,713 repeating earthquake sequences (RES) that include between 2 and 32 events with magnitudes between -0.5 and 6.5. Temporal behavior of the events within each RES ranges between random and quasi-periodic over the 30-year observation period and includes temporal clustering (bursts). The RESs occur throughout northern California, with some of the largest and most periodic sequences predominately, but not exclusively, along faults within the San Andreas Fault system that exhibit surface creep. Piecewise periodic RESs are found near large earthquakes where they are modulated by transient stress. Slip rates inferred from the new data, while generally consistent with published estimates from geodetic and surface data, offer a high-resolution image of subsurface creep along individual fault strands and resolve slip partitioning across wider zones of deformation. The new repeater catalog forms the baseline for routine detection and analysis of repeating events in real-time to help monitor changes in fault properties and loading rates.

Are Creep Events Big? Estimations of the Along-strike Rupture Extent of Creep Events Along the Central San Andreas Fault

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The San Andreas Fault has been observed to creep at the surface along the creeping section between San Juan Bautista and Cholame. Creep occurs along this creeping section at a steady background slip rate that is regularly punctuated by few-mm bursts of slip every few weeks to months. These bursts of slip are known as creep events. However, despite their abundance and observations of them beginning in the 1960s, we still do not know the rupture extent of creep events or the forces that drive them. So in this study, we systematically detect and characterize creep events in terms of their along-strike rupture extent.

We detect and analyze creep event rupture extent using 18 USGS creepmeters along the San Andreas fault. Using a cross-correlation approach, we systematically detect 2120 creep events in the creepmeter record spanning 1985 - 2020. We then compare the start times of these events to identify potential multi-creepmeter events and determine the frequency at which they occur. We identify 306 potential multi-creepmeter events, determine their potential along-strike length and assess the plausibility of these events. Through this visual inspection and statistical analysis, we identify five creep event types, including single-creepmeter events, small (<2 km) events, medium-sized (3-6 km) events, large (>10 km) events, and events that rupture multiple fault strands. To further assess the plausibility of these events, we repeated the analysis after removing events that may be driven by rainfall. We find that only the correlation of the largest creep events diminishes, suggesting that these kilometer-long events are not small rainfall-associated perturbations; they are likely to be driven by complex or heterogeneous frictional weakening at depth. We continue to investigate the properties of creep events further to better discriminate between the potential driving models of creep events.

Assessing Thermal and Hydrologic Conditions of Fault Creep in the Salton Trough From the Exhumed Sedimentary Section of the Fish Creek-Vallecito Basin

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The Salton Trough is a seismically active region in the northern Gulf of California right-lateral, transtensional rift system that is characterized by several upper-crustal, creeping strike-slip faults. High heat flow and overpressure conditions due to rapid sedimentation likely affect fault behavior within the Salton Trough, but direct observations at seismogenic depth are lacking. Rapid and recent uplift of the Fish Creek-Vallecito Basin (FCVB) and Vallecito fault, a subbasin and basin-bounding fault within the western Salton Trough, provides an exposure of the upper 4-6 km of crust, analogous to present crustal conditions at depth. The FCVB thus provides an opportunity to understand whether overpressure conditions developed at depth and to explore the effects of rapid sedimentation on the mechanical conditions of faulting, particularly fault creep, in the southern San Andreas fault system. The FCVB contains a continuous ~6 km sedimentary section deposited between 8 -1 Ma that was uplifted since ~1 Ma. However, the compaction of strata in the FCVB appears inconsistent with ~6 km burial, requiring an alternative structural model, anomalously high pore-pressure conditions, or both. We report new observations from the FCVB that suggest 1) the basin deposition and subsidence was partitioned between the hanging walls of the West Salton Detachment fault and the Vallecito fault, reducing the maximum burial depth and 2) the basin was cold (<55DegC) despite at least 4 km of burial. Though the sediments preserved within the FCVB are analogous to the Salton Trough, the geothermal gradient is much higher in the latter, which has been attributed to magmatic underplating and intrusions within the present-day rift axis. We present preliminary results from a one-dimensional model using a finite difference scheme to predict the evolution of excess hydraulic head and over pressure conditions during deposition of the FCVB.

Interseismic and Postseismic Creep Detected From Five Years of Sentinel-1 InSAR Data Over Northeastern Tibetan Plateau

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Knowing how much crustal strain is released through seismic versus aseismic processes is crucial for constraining the total seismic moment rate that must be accounted for by earthquakes. Therefore, detecting previously-unknown creeping sections and measuring their motion is important for seismic hazard assessment. Previous studies have mainly focused on known creeping sections often revealed by slowly displacing man-made infrastructure. However, such local-scaled studies do not allow us to systematically detect unknown creep. In this study, we process five years of Sentinel-1 satellite radar data to produce a large-scale 100 m-resolution east-west velocity field and 1 km-resolution strain rate fields over the 440,000 km^2 of Northeastern Tibetan Plateau. We detected two creeping sections along the Haiyuan Fault. The creep rate of the previously-identified Laohushan section has slowed down by 40-55% in comparison to rates measured between 1993 and 2009. In addition, we find its creeping motion to be fastest along the pull-apart Jingtai basin at a releasing step-over of the Haiyuan Fault, instead of along the straight and single-strand Laohushan section. This suggests that the pull-apart motion may have released the normal stress on fault, making the stress condition conducive to creep. Another section where we observed creep is along the Lenglongling Section, adjacent to the 2016 Mw 5.9 Menyuan Earthquake. The Menyuan Earthquake is understood to have only ruptured 20 km of a reverse fault attached at depth to the Haiyuan Fault. However, we observe a similarly high strain rate as that along the Laohushan section, over a distance three times the coseismic rupture, suggesting the reverse earthquake might have triggered postseismic creep along the strike-slip main fault. Our results demonstrate the role of large-scale high-resolution InSAR velocity and strain rate mapping in understanding the interplay of seismic and aseismic fault slip and for estimating seismic hazard.

Investigation of Fault Creep Variability Along the Southern San Andreas Fault

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Shallow fault creep has been observed on a number of faults in California including the southern San Andreas fault (SSAF). To better understand the spatiotemporal variability of fault creep along the SSAF, we analyze multiple satellite and airborne interferometric synthetic aperture radar (InSAR) data including ERS & Envisat, ALOS-2, Sentinel-1 and UAVSAR, which jointly span nearly three decades. We adopt a new approach that integrates GNSS to mitigate the atmospheric noise in the InSAR time series. Our analysis of multi-sensor InSAR data along with *in-situ* creepmeter measurements shows spatiotemporally varying transient behavior of surface creep along the SSAF. We develop laboratory-based rate-and-state friction models to investigate the controls on observed fault creep variation and how the shallow creep regime interacts with the seismogenic zone at depth. Our initial results show that shallow creep behaviors are prone to stress perturbations from tectonic/non-tectonic sources and that there is longer term transient fault creep behavior following large earthquakes.

Seismic and Aseismic Fault Slip During the Inter-seismic Period: Observations From the Marmara Region of the North Anatolian Fault

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The Marmara segment of the North Anatolian Fault Zone (NAFZ) represents a seismic gap with high probability for an M>7 earthquake near Istanbul. We investigate the distribution of seismic and aseismic deformation in the Marmara region compiling information derived from earthquake repeater identification and geodetic data analysis (strainmeters and GNSS). At the eastern portion of the Marmara segment, a locked fault was identified from absence of microseismicity and from GPS data. Towards the western part, shallow fault creep was reported based on sea-floor geodesy and the occurrence of repeating earthquakes in specific areas. We here generated a new 15-year homogenous seismicity catalog for the Marmara region (2006-2021) unifying the data from the main Turkish seismic agencies and including the GONAF network. A total of 13.876 events were of sufficient quality to obtain non-linear hypocenter locations. We utilized this catalog to search for earthquake repeaters along the entire Main Marmara fault segment and the southern Marmara and Armutlu faults. Centering at the Western High segment of the Main Marmara fault, a spatial transition eastward and westward from partially creeping to locked is observed based on the amount and magnitude of earthquake repeaters and the estimated creeping rate. Analysis of strainmeter continuous recordings revealed two slow slip events connected with the occurrence of two M4+ earthquakes in the region in 2016 and 2018 and lasting for at least 30 days. Coulomb forward modelling combined with seismicity analysis suggests that the fault source of these slip transients could be the shallower portion of a local normal fault structure in the Armutlu Peninsula favorably oriented with respect to the local stress field orientation. These results suggest that aseismic slip is occurring in some segments and different depth extents within the Marmara section of the NAFZ and that aseismic slip has a role in earthquake triggering in this region.

The Search for Dynamically Triggered Changes in Plate Interface Coupling and Implications for Fault Coupling Models

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Dynamically triggered coupling changes are a newly discovered phenomenon in which seismic waves from regional earthquakes cause enduring coupling changes on subduction zone plate interfaces. The most well characterized cases are two strike-slip earthquakes near Cape Mendocino, CA which triggered enduring coupling changes on the Cascadia plate interface (Materna et al., 2019). One earthquake triggered a coupling increase and the other a coupling decrease, both in the same location on the plate interface. Other probable cases of dynamically triggered coupling changes have been observed in Chile. (Jara et al., 2017; Melnick et al., 2017; Hoffmann et al., 2018).

Understanding dynamically triggered coupling changes is critically important for understanding earthquake hazards. Every coupling or locking model should be considered a snapshot in time, potentially subject to dynamically induced changes in coupling, as well as aseismic coupling release in the form of slow slip events, posteseismic transients and pre-earthquake accelerations (e.g. Mavrommatis et al., 2014). Additionally, the discovery of dynamically triggered changes in plate interface coupling implies that regions that appear uncoupled may have been previously coupled or may later become coupled, and thus may have future earthquakes contrary to the usual assumption that uncoupled regions do not host earthquakes.

Here I will summarize the current evidence for dynamically triggred changes in plate interface coupling, including pleliminary evidence for a third example in southern Cascadia that occurred in early 2020. I will also discuss a strategy and future plans for systemically detecting this phenomenon in other locations to better characterize how common dynamically triggered coupling changes are and better constrain the conditions under which this phenomenon occurs. This is turn will hopefully lead to a better understanding of how dynamic stresses are able locally change fault conditions and cause a switch between multiple stable coupling states.

Seismo-geodetic Approaches for Seismic and Tectonic Processes

Oral Session · Thursday 21 April · 2:00 PM Pacific

Conveners: Revathy M. Parameswaran, University of Alaska Fairbanks (rmparameswaran@alaska.edu); Dara E. Goldberg, U.S. Geological Survey (degoldberg@usgs.gov)

Imaging the Rupture Process and Postseismic Deformation of the 2019 Ridgecrest Earthquake Sequence with High-resolution Geodetic Data

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The 2019 Ridgecrest earthquake sequence was the most recent major seismic event to occur in the continental US, and its surface deformation was particularly well imaged by a dense network of Global Navigation Satellite System (GNSS) stations and several satellite radar interferometry (InSAR) missions. Combined with seismic recordings, these high-resolution surface deformation measurements provided essential constraints on the rupture process and slip distribution of the 2019 Ridgecrest earthquake sequence, including the triggering relationship between the Mw 6.4 foreshock on July 4 and the Mw 7.1 mainshock 34 hours later and the distribution of slip on the fault as a function of depth. However, we show that the published coseismic slip models of the 2019 Ridgecrest earthquake sequence exhibit large variations, despite the good coverage of both geodetic and seismic observations. This highlights the true uncertainties of the routinely performed earthquake rupture inversions and challenges the interpretation for underlying rupture processes. The 2019 Ridgecrest earthquake sequence also caused significant postseismic transient deformation in the surrounding areas. We show that at least three mechanisms, including afterslip, poroelastic rebound and viscoelastic rebound, are required to explain the postseismic deformation observed by InSAR and GNSS ~1.5 years after the mainshock. Specifically, the near-to-medium field postseismic GNSS and InSAR displacements are consistent with afterslip and poroelastic rebound, while the far-field GNSS data are best explained by viscoelastic relaxation in the upper mantle. The observed postseismic deformation due to poroelastic rebound also allows us to probe the hydrological properties of the shallow crust. In particular, the postseismic uplift near the mainshock epicenter can be well approximated by a poroelastic rebound model with a hydraulic diffusivity of ~0.1m^2/s in the top 2 kilometers.

Demonstrating the Utility of Seafloor Geodetic Instrumentation: A Case Study of the Simeonof-Sand Point-Chignik Earthquake Sequence Along the Alaska Subduction Zone

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Global Navigation Satellite System-Acoustic (GNSS-Acoustic) is a seafloor geodetic technique that combines acoustic ranging between the sea surface platform (typically an autonomous Wave Glider) and seafloor transponders with standard GNSS positioning to locate points on the seafloor to cm-level horizontal accuracy. GNSS-Acoustic is a powerful tool to measure horizontal seafloor offsets of subduction zones resulting from earthquakes such as the 2020-2021 earthquake sequence along the Shumagin segment of the Alaska subduction zone, including the 22 July 2020 Mw7.8 Simeonof, the 19 October 2020 Mw7.6 Sand Point and the 28 July 2021 Mw8.2 Chignik earthquakes. The proximity of these earthquakes to established GNSS-Acoustic sites presents a rare opportunity to add geodetic constraints on slip estimations from the seaward side of the earthquakes. In the months following each of the earthquakes, we deployed a GNSS-Acoustic Wave Glider to the nearest of three GNSS-Acoustic sites, which allowed us to measure the permanent seafloor offset trenchward of each earthquake. We present these GNSS-Acoustic position time series as well as fault slip models enhanced by the availability of these seafloor geodetic data. With the added GNSS-Acoustic data, we are able to infer shallow slip in the Simeonof and Chignik earthquakes not previously resolved with a kinematic inversion using only the sparse regional continuous GNSS and strong-motion accelerometer sensors installed on the nearby Aleutian Islands. We hope these results serve as a practical demonstration of how even minimal seafloor geodetic observations near the trench of a subduction zone can enhance our resolution of subduction zone behavior and motivate the further offshore instrumentation of subduction zones.

Validation of Peak Ground Velocities Recorded on Very-high-rate GNSS Against NGA-West2 Ground Motion Models

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Observations of strong ground motion during large earthquakes are generally made with strong-motion accelerometers. These observations have a critical role in early warning systems, seismic engineering, source physics studies, basin and site amplification and macroseismic intensity estimation. However, direct observations of velocity made with broadband seismometers often clip for large earthquakes in the near-field. Here we present a new observation of strong ground motion made with very high rate (>= 5 Hz) Global Navigation Satellite System (GNSS) derived velocities. To make these observations, we take a single difference in time between the orbital positions and the GNSS observables, specifically the narrow-lane combination of L1 and L2, to invert for the station velocities using the SNIVEL software package. We look at over 60 earthquakes and 600 station-event pairs for earthquakes between M4.9 and 9.1. We demonstrate that velocity observations recorded on GNSS instruments are consistent with existing ground motion models and macroseismic intensity observations. We find that the ground motion predictions using existing NGA-West2 ground motion models (GMM) match our observed peak ground velocities with a log residual less than the data used to derive the GMMs and are statistically significant following normality testing. We finish by showing how ShakeMaps for specific events are improved by adding this data into areas with previously sparse data coverage.

Expansion of Global GNSS-based Seismic Monitoring

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We continue to expand GNSS-based global seismic monitoring to now include ~ 1,600 GNSS receivers that can rapidly characterize large earthquakes and, where relevant, tsunami. This new system complements traditional seismic monitoring by allowing moment release to be quantified while fault rupture unfolds. Position time series from stations distributed across six continents are continuously estimated within an earth center of mass-fixed reference frame and streamed as local north, east and vertical coordinates into a variety of seismic monitoring algorithms and also rebroadcast for third-party use. Average positioning latency, which includes satellite observable acquisition, telemetry and processing, averages about 0.52 seconds on our production system and 1.2 seconds. The analysis system has been operating uninterrupted for over five years with less than one hour total downtime. We aim to up the number of global stations to ~2500 in 2022.

This system works. It captured the 2019 Ridgecrest California M7.1 earthquake and determined its coseismic deformation of up to 70 cm on 12 nearby stations within 22 seconds of event nucleation. Those 22 seconds comprise the fault rupture time itself (roughly 5-10 sec), another ~5s for propagation delay between various regions of slip and GNSS stations, another 5-10s for dynamic displacements to dissipate such that coseismic offsets 'settle down,' plus another 1.4 seconds for telemetry and data analysis latency. Comparison of coseismic deformation estimated within 25 seconds to that determined with post-processing using several days of post-processing show that the real-time offsets were accurate to within 10% of the post-processed "true" offsets. While ~1 sec determination of GNSS coseismic offsets could not help ShakeAlert improve its initial magnitude assessment made several seconds after nucleation, high-M6 magnitude at ~25 seconds could have helped revise alerts before S-waves reached the LA. This highlights how GNSS can improve characterization of events whose duration or extent of rupture is difficult using P-wave amplitudes.

Impart of Three-dimensional Structure of Subduction Zone on Time-dependent Crustal Deformation Measured by HR-GNSS

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Current high-rate Global Navigation Satellite System (HR-GNSS) models use simplified 1D radially symmetric Earth models. However, for shallow subduction zone earthquakes, shaking is likely affected by many strongly heterogeneous structures such as the wedge, the slab and the overlying crustal structure. We aim to understand how including such 3D structure of a subduction zone impacts the time-dependent crustal deformation measured by HR-GNSS. To this end, we compute 1D and 3D synthetic, 0.5Hz waveforms at HR-GNSS records of 5 M6.6+ earthquakes in Japan. For every earthquake, we use 1 or 2 rupture models from FakeQuakes and make <0.5Hz waveforms at the GNSS locations. We perform forward models of 3D kinematics and the crustal deformation of earthquakes using SW4. SW4 software solves the seismic wave equations in displacement formulation using a 4th Order Finite

Difference method for 3D velocity structure models. We compute various intensity-measure residuals of the synthetics to the observed GNSS waveforms and compare the 3D residuals with those determined using 1D velocity models. Our results will help understand if 3D simulations are necessary for kinematic and crustal deformation studies and will in particular be applicable to tsunami earthquakes. Improving models of GNSS waveform characteristics will help understand the underlying processes and improve the warning of tsunami earthquakes.

Seismo-geodetic Approaches for Seismic and Tectonic Processes

Poster Session · Thursday 21 April · Conveners: Revathy M. Parameswaran, University of Alaska Fairbanks (rmparameswaran@alaska.edu); Dara E. Goldberg, U.S. Geological Survey (degoldberg@usgs.gov)

Earthquake Detection Sensitivity of GPS Time-differenced Carrier Phase Velocities

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Current geodetic contributions to the USGS ShakeAlert Earthquake Early warning system are relative displacements from precise point positions (PPP). These displacements are able to provide unsaturated, rapid magnitude estimates of larger earthquakes given existing empirical scaling laws relating the peak of these displacements at a given radius and magnitude of an earthquake. A quasi-independent geodetic processing method is time-differenced carrier phase (TDCP) velocity estimation, which unlike PPP does not require complex correction services. Our efforts build on previous work to estimate the ambient noise of TDCP velocities calculated using the SNIVEL software package and determine their detection sensitivity, given station-dependent ambient thresholds relative to existing scaling laws. We compare the ambient sensitivities of these two processing approaches for concurrent time and station combinations. We find that the TDCP velocities have increased sensitivity to smaller signal amplitudes with increased rapid magnitude estimate variance relative to PPP displacements. Additionally, we compare the performance of these methods in several existing earthquake datasets. Our findings align with concurrent efforts that suggest TDCP velocities could be a readily available, complementary data product for rapid earthquake detection and characterization.

Generation and Validation of Synthetic HR-GNSS Data for New Zealand Megathrust Rupture Scenarios

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New Zealand's vulnerability to seismic and tsunami hazards represents a pressing concern to inform the community when an earthquake occurs in the future. New Zealand has a robust real-time seismic and geodetic network capable of monitoring moderate-to-large earthquakes and recently received a 5-year grant to move the networks towards full automation with an end goal of local tsunami warning. We aim to test approaches that can obtain a rapid characterization of large earthquakes with the aid of Global Navigational Satellite Systems (GNSS) data. Here, we use a database of 350 megathrust ruptures obtained from an earthquake cycle model of the Hikurangi subduction zone using RSQSIM, to generate synthetic displacement data at all currently operating real-time sites in the country. We validate the synthetic data against known Peak Ground Displacement (PGD) ground motion models. We then ingest this data into G-FAST, a rapid source characterization suite that can yield rapid magnitude and slip distribution estimates, to show the efficacy of G-FAST in characterizing these events with the current network configuration in New Zealand. We finish by showing some examples of how the G-FAST results can produce tangible tsunami warnings in the region.

Multifractal Analysis of Point Source Distributions Obtained From InSAR Inversion

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We apply a point source inversion technique to one and two-dimensional ground deformation data obtained from InSAR interferograms containing signals from large earthquakes. Our method defines a grid of point sources, each of which causes ground deformation according to Okada's equations for surface deformation in an elastic half-space. We invert the ground deformation data to obtain the seismic moments of the point sources in order to find the distribution that best mimics the ground deformation seen in the InSAR interferogram. After the inversion, we investigate the fractal properties of the point source distributions by removing sources below a certain threshold of slip and seeing how the distribution varies as we vary the threshold. The target earthquakes in this study are the mainshock of the 2015 Gorkha earthquake in Nepal and the 2017 Iran-Iraq earthquake.

Reconciling Seismic and Geodetic Magnitude Estimates for Rapid Earthquake Characterization

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Rapid magnitude estimation following a damaging earthquake is vital to emergency response. Magnitude determination using peak ground velocities (PGV) derived from Global Navigation Satellite Systems (GNSS) is a promising method that is in development. Furthermore, network-wide GNSS-derived PGV-interpolation could also inform estimates of ground motion, complementing data typically derived from strong motion accelerometers. This begs the question of how GNSS-derived PGVs compare to near-field seismic observations. Our study compares GNSS-derived PGVs to those computed from strong-motion records, while also evaluating GNSS-derived ground accelerations (and peak ground accelerations, PGAs) to the strong-motion time series. In light of the recent 2021 Mw 8.2 Chignik earthquake in Alaska, we apply these concepts to co-located and closely-located GNSS and strong-motion sensors. We aim to understand PGV-derived magnitude evolution using both seismic and geodetic data, the roles of frequency content, signal-to-noise ratios (SNRs) and how to effectively incorporate the two data sets in rapid earthquake characterization in the context of the Chignik event.

Spatiotemporal Variations of Stress and Strain in the Crust Near 2019 Ridgecrest Earthquake Sequence

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We analyze 2 years postseismic deformation of the 2019 Mw 7.1 Ridgecrest earthquake sequence employing both seismic and geodetic data including InSAR and GPS. We use geodetic data to measure the postseismic surface deformation and infer the associated afterslip, in addition to image pre-earthquake deformation. The interferograms are obtained from ARIA (Caltech-JPL Advanced Rapid Imaging and Analysis) products, which has been systematically processing InSAR data from the Copernicus Sentinel-1 satellites. Two tracks of C-band SAR data cover the study area, recording more than 30 interferograms from each of the ascending track 64 and the descending track 71 every 6 and 12 days. GPS data are obtained from GeoGateway, which is a data product and analysis tool developed by NASA consisting of geodetic imaging products. The estimated postseismic deformation is consistent with the main right-lateral NW-SE rupture. The largest surface uplift and the largest displacement in the afterslip model are located near the Mw 7.1 hypocenter. We also examine the associated stress field inverting more than 4,500 fault plane solutions within the same postseismic time period and estimate the 4D spatiotemporal stress field variations in the study area. Overall, the stress field estimations indicate higher extensional stress components in the NW of the main rupture shifting to higher compressional components in the SE adjacent to the Garlock fault. The spatiotemporal stress field evolution during the postseismic period shows the largest variations in the upper 4 km of the crust, indicating the heterogeneous brittle region and the least variations deeper than 8 km indicating higher viscoelastic component near the brittle-ductile transition zone. Integrating the obtained afterslip, strain-rate and stress field, we investigate locations with higher variations in the strain-rate and stress

field to detect zones that are potential for higher stress accumulations and seismic hazard.

Tectonic Tremor Used as a Proxy for Slow Slip Can Be Used to Remove Its Effect From a GNSS Signal and Reveal Changes Due to Annual Rainfall

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The vertical component of Mexican GNSS stations have a cyclic displacement that matches annual rainfall. The rainfall dominates the vertical component so that long term signals such as slow slip events (SSE) are difficult to observe within the signal. Horizontal components appear to not contain the same annual effect as large long-term slow slip signals are clearly observed in them. However, if the vertical component is clearly affected, horizontal components may be affected too. We use tremor to remove the slow slip events and reveal the effect of annual rainfall in horizontal components. Robust many-year tremor catalogs have been previously developed using the permanent seismic stations. These catalogs have been shown to generally match the long-term displacement of the N-component at GNSS stations. We determine a relation between the accumulated tremor catalog at a seismic station near Iguala and the mm displacement measured on the N-component at the co-located GNSS station (0.15 mm/hour). We then use this relation to convert the tremor catalog to mm displacement. We then remove the tremor catalog from the N-component of the GNSS signal. The result shows an annual 5 – 10 mm cycle that follows the rainfall. There is a water reserve to the south of the station. We model how changes in water load during the rainy and dry seasons strain the ground. The model suggests that it can be the cause of the observed signal in the horizontal components. We do not observe signals in the horizontal components that coincide with the annual rainfall at other geodetic stations suggesting that the reservoir at this station causes a unique effect.

Shakes in Lakes: Frontiers in Lacustrine Paleoseismology

Oral Session · Thursday 21 April · 2:00 PM Pacific

Conveners: Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Maarten Van Daele, Ghent University (maarten.vandaele@ugent.be); Jamie Howarth, Victoria University of Wellington (jamie.howarth@vuw.ac.nz)

Towards a Paleoseismic Record of Intraslab Earthquakes in the Alaskan Subduction Zone

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Paleoseismic records of Alaskan subduction zone earthquakes currently rely on coastal marsh records. While these are extremely valuable for reconstructing megathrust earthquake recurrence, they do not provide direct information on shaking and therefore cannot record intraslab earthquakes, which do not cause land deformation. In contrast, sedimentary records preserved in lakes above subduction zones may—apart from megathrust earthquakes—also register evidence of intraslab earthquakes in the form of shaking-triggered turbidite or landslide deposits, when Modified Mercalli Intensities (MMI) reached values of ≥V½. Consistent with this hypothesis, we identify turbidites related to the recent M_w 7.1 2016 Iniskin and 2018 Anchorage earthquakes in the lakes studied here. We present a 2.3 kyr landslide- and turbidite-based paleoseismic record of two proglacial lakes: Skilak and Eklutna Lake, located in the zones of strong ground motion in 2016 and 2018, respectively. High-resolution varve-based age models link several lacustrine slope failure deposits to the known megathrust earthquakes that left coastal evidence in the Prince William Sound, Kenai and Kodiak sections of the megathrust. To validate these correlations, we calculated the paleo-MMI for each of these earthquakes by means of intensity prediction equations (IPEs). Similarly, we used IPEs to identify which crustal earthquakes—independently known from fault trenching—caused an MMI of ≥V½ and are thus potentially recorded in the lakes by means of turbidites or landslides. We therefore postulate that the majority of the remaining earthquake-triggered turbidites are the result of intraslab earthquakes that caused shaking at the lakes similar to, or more intense than, that resulting from the 2016 and 2018 earthquakes. These new records thus provide paleoseismic records of intraslab earthquakes, which are not identified in the coastal marsh records and provide insight into their recurrence.

Using Lacustrine Paleoshaking Evidence to Quantitatively Determine Earthquake Source Parameters

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Lacustrine paleoseismology has proven an invaluable tool to adequately reconstruct the seismic shaking history of a particular region, especially along subduction zones where the seismic hazard is multifold. One of the main strengths in such studies lies in the application of a multi-lake approach, in which spatio-temporal correlation of sedimentary shaking evidence allows distinguishing imprints related to large-scale megathrust earthquakes from those caused by locally intense intraplate shaking. Unfortunately, the relationship between local ground motions and earthquake source parameters such as magnitude and rupture location—both of which are crucial for adequate seismic hazard assessments—is usually inferred by considering qualitative rather than quantitative constraints. To overcome this drawback, we developed a methodology based on the principles of probabilistic seismic hazard assessment and ground motion modelling. To explain an observed spatial distribution of sedimentary shaking imprints (or the lack thereof) for a particular paleoearthquake, we infer the minimum and/or maximum shaking intensity that must have been achieved at each location. The probability that an earthquake with a specific magnitude in a certain location produces ground motion levels that fall within the range defined by these minimum and maximum thresholds is then calculated by application of a suitable ground motion prediction equation (GMPE). To illustrate these concepts, we present a case study from a ~4400 year old earthquake, identified in the Chilean Andes in Lago Castor and Pollux as well as in Aysén Fjord. The methodology has thus been successfully applied to crustal earthquakes, for which fault geometry, morphology and length are well-constrained and rupture variability is limited. In the near future, we aim to apply the same principles to megathrust earthquakes by also taking into account variability in, for example, rupture depth, length, directivity and slip distribution.

Lakes as Paleoseismic Records in a Seismically-active, Low-relief Area: An Example From the Rieti Basin, Central Italy

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Small lakes in low relief areas are atypical candidates for studies on paleoseismicity, but their sediments can contain seismically induced event layers that are generated through strong ground shaking, sediment transport, hydrological reorganization and/ or changes in groundwater chemistry and flow. Co-seismic movement near low relief lakes can change lake inflow and outflow and in proximal settings can produce seiche waves that can disrupt, resuspend and refocus sediment. Additionally, when lakes receive hydrologic inputs from multiple hydrochemically distinct sources, there is a potential for seismicity to alter the relative contributions of these inputs.

Lakes Lungo and Ripasottile are shallow lakes (<10m deep) located adjacently in the tectonically active Rieti Basin in the central Apennines, Italy, where strong normal faulting earthquakes (Mw 6.5 to 7.0) regularly occur. Sedimentological and geochemical analysis from lake cores representing the last ~1000 years reveal four event layers, identified in both lakes, that corre-

spond with >6 magnitude earthquakes having epicenters within 40km of the lakes. These events occurred in 1298, 1349, 1639 and 1703 AD. The common physical structure is a homogenous bed of re-suspended sediment consisting of a denser, high magnetic susceptibility (MS) clastic base, with organic matter concentrated above. Co-seismic to post-seismic chemical signatures are associated with some but not all event layers and may represent abrupt or transient shifts to a groundwater-dominated system with increased inputs from the high sulfate karstic aquifer, or permanent changes in groundwater flow and/ or spring discharge. Excursions in $\delta^{13}C_{org}$ may represent disruptions or changes in carbon source. Not all event layers show the same features, a result attributed to differences in seismic processes as well as the lake attributes and anthropogenic modification. The observations made here may provide a new means of detecting paleoseismicity, add potential for event stratigraphy correlation and be applied to other low relief lakes in seismically active areas.

Sedimentological and Geochemical Characterization of Earthquake-generated Turbidites in Fault-proximal Glacial Lakes of the Teton Range, Grand Teton National Park, Wyoming

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Lakes in seismically active regions present valuable sedimentary archives of paleoseismic activity within their catchment and beyond. A series of glacially-excavated lakes positioned directly along the surface trace of the Teton fault at the base of the Teton Range, WY, are ideally situated to record past fault activity since their formation ~15,000 years ago. The Teton fault is a major range-bounding normal fault that is recognized as one of the more active and hazardous faults in the Basin and Range Province, but which is also noted for its irregular postglacial paleoseismic history and relative quiescence during historical time. Previous work has demonstrated that earthquake events are registered in Teton lake sediment sequences as distinct, basin-wide turbidite deposits that can be identified visually in core section and through changes in sediment physical character. Importantly, the ages of these diagnostic deposits can be correlated between multiple lakes and to the timing of surface rupturing earthquakes identified in fault trenches. We leverage this well-constrained system to conduct a detailed study of prominent turbidites in Jenny Lake at high-resolution to develop a better understanding of the stratigraphic expression of past earthquakes in Teton lakes. Jenny Lake is a relatively large (5 km^2) and deep (~75 m max depth, ~45 m mean depth) glacially-carved basin located at the bottom of Cascade Canyon in the central Tetons, where post-glacial slip rates are greatest. In this study, we focus on the five thickest turbidites (ranging from ~5 to ~25 cm thick) and analyze them at sub-centimeter resolution for changes in grain size distributions, elemental compositions and physical sedimentology. Based on our analyses, we create an interpretive model of turbidite formation and characterize sediment sources and transport pathways during past earthquake events. We further present emerging paleoseismic histories developed from three other nearby Teton lakes.

Lacustrine Paleoseismic Records of Cascadia Megathrust Earthquakes From Lake Ozette, Washington

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Lakes often contain the high-fidelity sedimentary proxies needed to reconstruct the timing of punctuated shaking from large earthquakes and other hazards typical along active continental margins. Here we present evidence for earthquake-triggered mass transport deposits (MTDs) in Lake Ozette, Washington, a ~100 m deep coastal lake located along the outer coast of the Olympic Peninsula. Lake Ozette is likely situated above the locked portion of the northern Cascadia megathrust and is relatively isolated from active upper-plate faults. The USGS led two field campaigns in 2019 and 2021 to acquire high-resolution bathymetry, sub-bottom profiles and sediment cores to develop three-dimensional constraints on Ozette's sedimentation history for at least the last 10 ka. Several sub-basins separated by bathymetric sills characterize the basin physiography; the eastern sub-basins are proximal to fluvial catchments and small subaqueous deltas; the western sub-basin is isolated from any significant fluvial sediment sources. The basin floor near the deltas is blocky, rugged and appears to be covered in MTDs. Chirp profiles image a succession of up to twenty-nine stacked high-amplitude layers that onlap surrounding slopes. Sediment cores sampled to a depth of 14 meters, bottoming out in coarse grained glacial outwash deposits and confirm these high-amplitude layers are discrete, normally graded sand beds (turbidities). Core sites within distal basins contain massively bedded, organic-rich silt/mud layers; each corresponds to one of the sand layers in the proximal basins. These deposits appear to have been triggered by subaqueous slope failures during megathrust ruptures. More than 50 radiocarbon dates of terrestrial plant fragments are used to constrain the ages of the youngest 11 turbidites (last ~5.5 kyr BP), yielding a recurrence interval of ~500 years. Lake Ozette may contain the most complete record (~29 events) of subaqueous MTDs generated by large megathrust ruptures along this portion of the Cascadia subduction zone.

Shakes in Lakes: Frontiers in Lacustrine Paleoseismology

Poster Session · Thursday 21 April · Conveners: Peter J. Haeussler, U.S. Geological Survey (pheuslr@usgs.gov); Maarten Van Daele, Ghent University (maarten.vandaele@ugent.be); Jamie Howarth, Victoria University of Wellington (jamie.howarth@vuw.ac.nz)

Are Wasatch Front Earthquakes Preserved in the Great Salt Lake Sedimentary Record?

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The Great Salt Lake (GSL), Utah (USA) occupies fault-bounded subbasins in the Wasatch Front region and offers a unique opportunity to explore how lacustrine sediments in a low-relief, endorheic basin respond to earthquake shaking. Historical earthquakes, such as the 2020 M5.7 Magna earthquake and terrestrial paleoseismic data for the nearby Wasatch fault, make the region ideal for interpreting the sedimentary signatures of both historical and prehistorical earthquakes. To investigate whether earthquakes are preserved in the GSL sedimentary record, and if so, the dominant mechanisms of sediment disturbance, we collected 420 line-km of subbottom Chirp data and 38 mini hammer cores (each 6 cm in diameter and 81–189 cm in length) west of Antelope Island in the south arm of the GSL. The Chirp profiles image the uppermost 20–30 m of unconsolidated lake sediment at 12–15-cm resolution, and we interpret laterally continuous seismic stratigraphy, faulting, rotation and post-event sediment onlap and growth. X-ray computed tomography (CT) density scans, bulk-density measurements and photo logs of the cores reveal finely laminated to cross-bedded sediment. In the cores, we document sediment disturbance structures including folded beds, brecciated layers and brittle deformation that likely reflect prehistorical and historical shaking. Downslope of a sand spit, we observe ~10–20-cm thick sand beds that are laterally continuous, lack internal structure, generally fine upwards and could represent earthquake-related mass-transport deposits. Locally, cross-bedded sediments suggest wave-related sediment transport and poor preservation of any earthquake signal. We plan to relate spatiotemporal patterns of sediment disturbance and transport to earthquake-related unconformities interpreted in the Chirp profiles. These results, when integrated with terrestrial paleoseismic data, will help resolve the degree to which the GSL acts as a Wasatch Front lacustrine seismograph.

Constraining the Initiation, Spatial Distribution and Sedimentary Source of Lake Turbidites Triggered by the 2018 Anchorage Earthquake

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Alaska is frequently impacted by intraslab earthquakes, which occur at depths of 40 to 100+ km and do not produce the typical surface faulting, land-level change, or tsunami deposits associated with crustal or megathrust earthquakes. The emerging field of lacustrine paleoseismology, which utilizes well-defined basins, unique depositional characteristics (i.e., varve formation) and earthquake-generated sediment proxies has the potential to reconstruct intraslab earthquake histories. We present results of a multi-lake field campaign that used short-barrel gravity cores and high-resolution Chirp data to investigate the spatial extent of seismically triggered turbidites from the 2018 Anchorage earthquake. By targeting lakes at varying epicentral distances from the 2018 earthquake we were able to observe the cessation of shaking induced remobilized sediment, which appears to converge towards a minimum shaking intensity threshold of MMI ~5.5. Stream deltas appear to be more susceptible to strong ground motion than basin slopes, producing thicker turbidites and in most environments appearing to fail at lower shaking intensities than nearby hemipelagic slopes. However, in Skilak Lake, grain size analyses suggest that sediment remobilization occurred on basin slopes that experienced an MMI of ~5.5, highlighting the importance of calibrating different lake basins to strong ground motion. Additionally, in Skilak Lake, a sampled turbidite deposit records shaking during the 2016 Iniskin earthquake (also an intraslab event), suggesting that deep proglacial lakes, such as Skilak, may not require a significant slope recharge time between events. The results of this study provide a lower bound for the minimum amount of shaking necessary for an observable turbidite deposit to be produced and will be important for further ongoing efforts to expand the Alaskan earthquake record through the Holocene.

Developing a Chronology of Crustal and Megathrust Earthquake Records in the Pacific Northwest: Preliminary Results from Lakes Whatcom and Sammamish in Washington

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The potential for megathrust earthquakes and tsunamis along the Cascadia subduction zone, along with crustal and intraslab earthquakes, poses an array of complex hazards for the Pacific Northwest (PNW). However, large uncertainties in event timing from existing coastal and marine records makes it difficult to fully assess the hazards. Lacustrine environments record sensitive paleoseismic proxies that can resolve discrepancies in existing chronologies and paleoshaking intensities. The USGS is engaged in a multiyear effort to examine records of ground motion through systematic investigation of lake basins across the PNW that will allow us to distinguish earthquake sources, determine the shaking thresholds for sediment remobilization and develop a regional paleoseismic record.

We present preliminary results from newly acquired swath bathymetry, Chirp subbottom data and sediment cores across two lakes in the Puget Sound region, Lake Whatcom and Lake Sammamish. Lake Whatcom is steep sided with multiple subbasins and up to 20m of stratified Holocene sediment emplaced above thick, massively bedded Late Pleistocene layers. The Holocene strata are punctuated by numerous turbidites and occasional thicker mass transport deposits at the bases of steep slopes. Lake Sammamish has a single basin that overlies the Seattle Fault on the southern end. The surrounding hillslopes have numerous subaerial landslides with subaqueous deposits. Some of these failures have been previously correlated with the AD 900–930 rupture of the Seattle Fault (Prunier, 1998). Lake Sammamish also has robust turbidite stratigraphy with key ash marker beds. Submerged tree stumps and widespread erosional surfaces indicate highly variable lake levels. Upcoming work will expand eastward, targeting a series of lakes in the Cascade arc to test basin sensitivity to ground motions and determine the spatial extent of earthquake records associated with different types of crustal and megathrust rupture events.

Hunting For Norway's Biggest Historical Earthquake

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There exists an apparent spatial discrepancy between the well-documented very-large-magnitude earthquakes that occurred in early Holocene Fennoscandia and the generally-low-magnitude seismicity of the instrumental record. One reasonable conceptualization is that early Holocene Fennoscandia was a) initially characterized by a relatively short, abrupt pulse of high-magnitude seismicity directly related to dissipation of the Scandinavian Ice Sheet and b) at some point thereafter underwent a transition to the generally-low-magnitude, perhaps-far-field-driven seismogenesis of today. If such a transition were to have occurred early in the Holocene, for example, ca. 7–8 ka BP, today's earthquake distribution would likely reflect Fennoscandia's long-term seismic budget. However, it is not certain that such a transition took place—or if it did begin, whether the change from one regime to another has been completed.

One reason behind this uncertainty is the general lack of high quality, regionally comprehensive paleo-seismic data. However, lake basins contain some of the most numerous and widespread post-glacial sedimentary records in mainland Norway. We are attempting to exploit this dataset by documenting sedimentological and paleomagnetic evidence for the biggest historical earthquake known to have occurred in Norway. Although the magnitude of this 1819 event on the mid Norwegian coast has been debated, there is general agreement that it was a powerful event. The shock may have been felt as far south as Stockholm; near the estimated earthquake epicenter a suite of rockfalls, landslides, unusual waves and people having difficulty standing were reported. A successful resolution of our proof-of-concept would unlock a vast repository of Holocene paleoseismic data with which to better understand Norwegian seismogenesis.

Investigating Earthquake Rupture History of the Cascadia Subduction Zone Using Coastal Lacustrine Diatoms, Lake Ozette, Washington, USA

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Tidal wetland stratigraphy and offshore turbidite records at the Cascadia subduction zone (CSZ) preserve exceptional geologic evidence of coseismic land-level changes and tsunami inundation from past great (M_w >8) earthquakes. Onshore and offshore records document up to 18 great earthquakes over the last 10,000 years, but most onshore evidence is concentrated in the central and southern CSZ where records extend thousands of years longer than the northern CSZ. The limited onshore record of past earthquakes and tsunamis in the northern CSZ, as well as differing preservation thresholds for geologic evidence and dating uncertainties leave questions about the spatial and temporal variability of past events. Earthquake magnitude thresholds for generating depositional signatures in lakes are typically lower (MMI ~5.5) than other environments, suggesting that lakes may contain a more complete picture of regional shaking history.

Lake Ozette, located on the coastal rim of the Olympic Peninsula in Washington State, contains more than 25 Holocene subaqueous mass transport deposits (MTDs) that appear to have been emplaced during strong shaking events (see Brothers et al.– this session). The last 11 MTDs can be dated and correlated to other onshore and offshore geologic records of great earthquakes along the CSZ. Here, we explore whether microfossils, such as diatoms, preserved within Lake Ozette sediments may provide an independent test of the seismic origin of inferred MTDs (versus hydroclimatic origins). We investigate the diatom signature across potential MTD contacts in order to characterize source sediment and differences between the MTDs and the alternating lake bottom sediments. The broad scale implications of this research are to understand the recurrence interval of great earthquakes along the CSZ, improve spatial correlation of seismic events and enhance the earthquake record for Cascadia by discovering events that could be recorded in lacustrine sediments, but not as easily in the coastal stratigraphic record.

Preliminary Lacustrine Paleoseismology From Chelatna Lake, Southcentral Alaska, From Chirp Profiles and Short Cores

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We examined Chelatna Lake in southcentral Alaska as a potential recorder of the 2018 M7.1 Anchorage earthquake and to evaluate the seismic history of the region. This lake is located at the southern edge of the Alaska Range approximately 160 km northwest of Anchorage and about 90 km above the subducting Pacific plate. It is a proglacial lake that fills a single basin (max water depth of ~145 m). We surveyed the lake in June of 2021 using a modified cataraft developed by the USGS for remote lake studies. We collected 28 hammer-gravity cores up to 1.8-m-long and 120 line-km of high-resolution Chirp data. The cores were CT (computerized tomography) scanned, run through a multi-sensor-core-logger and photographed. The cores consist of alternating light-dark couplets, which are composed of a coarse-grained base and a winter clay cap. We interpret Cs-137 and Pb-210 geochronology as indicating the couplets are annually deposited varves typically 1.2 mm thick. Interrupting these varves are thicker (~5-500 mm) normally graded units, which we interpret as turbidites. We subdivide the turbidites into two types based on color. There are frequent darker, thinner deposits, which we interpret as flood deposits, and less common lighter, thicker deposits, which we interpret as having a seismic origin. Based on the preliminary varve year and radionuclide age model, we tentatively identify three historic earthquakes in the Chelatna sedimentary record: the 2018 and 1991 intraslab events and the 1964 megathrust event. Below the recent historical period, the cores show several thicker turbidite deposits of probable earthquake origin. Below the coring depth, the high-resolution Chirp data show three large (0.5-6 m thick) laterally continuous packages of homogenous to chaotic reflections with geometries consistent with mass transport deposits, possibly of seismic origin. It appears Chelatna Lake holds a valuable record of earthquake shaking of southcentral Alaska.

Site Response Characterization in Seismic Hazard Analysis

Oral Session · Friday 22 April · 8:00 AM Pacific

Conveners: Behzad Hassani, BC Hydro (behzad.hassani@bchydro.com); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Sean K. Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Gail M. Atkinson, Western University (gmatkinson@aol.com); Anna Kaiser, GNS Science (a.kaiser@gns.cri.nz); Marta Pischiutta, Istituto Nazionale di Geofisica e Vulcanologia (marta.pischiutta@ingv.it); Jonathan P. Stewart, University of California Los Angeles (jstewart@seas.ucla.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin@gfz-potsdam.de)

Evaluation of the P-wave Seismogram Approach to Estimate Vs30 in California

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The P-wave seismogram method infers near surface shear wave velocity from earthquake ground motion recordings. As a result, it can be used to estimate the shear wave velocity at sites where in-situ measurements are not available. To further evaluate the accuracy of the P-wave seismogram method for regions other than Japan and Central and Eastern North America (CENA), the approach is utilized to estimate the Vs30 of 194 stations in California. The comparison of measured and estimated Vs30 values shows that 85% of stations have an estimated Vs30 value within ±50% range of measurement, validating the reliability of the P-wave seismogram method in estimating Vs30. Comparing the Vs30 estimations from this study to the geology and slope based Vs30 map suggests that the P-wave seismogram method achieved less dispersion relative to measured Vs30 than the proxy-based method. However, stations with average measured Vs30 greater than 500 m/s may be overestimated by the P-wave seismogram method. This is suspected to be because the P-wave seismogram approach averages the shear wave velocity over a certain depth and thus captures velocity contrasts at medium or deep depth that are not reflected in the Vs30. The Horizontal-to-Vertical Spectral Ratio (HVSR) is proposed in this study to help identify sites with potential bias due to this issue. Additionally, the effect of using a more detailed crustal model for California is examined, and the result indicates that when the more detailed crustal model is used the Vs30 tends to be underestimated for events with focal depth less than 2.5 km, which is due to the layers with low P-wave velocity and steeper gradients of P-wave velocity at shallow depths in the more detailed crustal model.

Estimation of Vs30 using the P-wave Seismogram Method in California, USA

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A time-averaged shear wave velocity of the top 30-meter soil deposit (V_{S30}) is a well-known parameter for earthquake ground motion amplifications and engineering design. It can often be obtained by various field tests such as spectral analysis of surface wave (SASW) and array microtremor (AM). When these tests are not available, several proxies such as ground slope, surface geology and geotechnical categories can be used for estimating V_{S30}. However, these proxy-based estimates are usually associated with significant uncertainty. Kim et al. (2016) proposed an efficient and accurate method for estimating V_{S30} using P-wave seismograms. We applied the P-wave method to estimate V_{S30} values at the recording stations in California, USA.

In this study, we estimate V_{S30} values at 56 stations that have measured shear wave velocity profiles (Yong et al. 2013). We used a total of 706 seismograms collected from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. We rotate two horizontal component ground motions to the radial direction and identified the arrival times of the P waves. We calculate signal-to-noise ratios (SNRs) and remove motions with SNR > 2. We compute the ratio of the initial amplitudes in the vertical to horizontal directions and estimate average shear wave velocity from the ground surface to a certain depth, z (V_{SZ}). To convert V_{SZ} to V_{S30}, we develop linear relationships between V_{SZ} and V_{S30} for various depths (up to z = 240m), using 845 shear wave velocity profiles in California (Boore et al. 2003, Kayen et al 2005, Yong et al 2013, Thompson et al 2010). We compare the measured and the estimated V_{S30} values. The standard deviations of the total, between-site and within-site residuals are 0.45, 0.34 and 0.32, respectively. The standard deviations of between-site residuals for the slope-proxy method (Wald and Allen, 2007) and geology-proxy method (Will and Clahan, 2006) are both 0.4 for the stations used in this study. This indicates that the P-wave seismogram method can be used to estimate V_{S30} in California.

Evaluation of the Vs30-Kappa Relationship for Anchorage, Alaska

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Anchorage, Alaska is situated in one of the most active tectonic regions on the globe. Sitting at the edge of the North American plate and subducting Pacific plate, this region experiences intraslab and interface earthquakes, as well as crustal earthquakes. Anchorage was significantly damaged as a result of the 1964 M_W 9.1 1964 Great Alaska earthquake and more recently, the 2018 M_W 7.1 Anchorage earthquake. Over the past two decades hundreds of M_W 4.5 or greater magnitude earthquakes have been recorded by dozens of strong-motion stations within Anchorage. Recently, research has been presented showing time-averaged shear wave velocity estimates of the upper 30m (V_{S30}) using a suite of 95 events of greater than M_W 4.5 and less than 300km from Anchorage. In addition to the utilization of V_{S30} for initial site response analysis, the parameter Kappa (κ_0) is considered a near-site attenuation parameter and can be used to further constrain site response analyses. As an extension of the previous V_{S30} work, we have evaluated Kappa for selected earthquake events and utilized the V_{S30} estimates for the strong-motion stations to evaluate and develop a V_{S30}-Kappa relationship for Anchorage. Using the results of this analysis we revisit several strong-motion sites, based on their V_{S30} estimate and evaluate the appropriateness of V_{S30} to estimate site response.

Estimating Shallow Shear-wave Velocity Profiles in Alaska Using the Initial Portion of P-waves From Local Earthquakes

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The Alaska Regional Network and Transportable Array provide an invaluable waveform dataset for studying ground motions in Alaska. However, the dataset is useful only after the site effects at each station are well understood. Considering the large number of stations associated with these networks, it would be onerous to measure the sub-surface velocity structure beneath every station using geophysical exploration techniques involving arrays, such as

ReMi and MASW. It has been demonstrated that the ratio of radial to vertical P waves (receiver method) is mostly sensitive to sub-surface shear velocity. We applied this approach to data from the AK permanent seismological network as well as the Transportable Array to estimate the time averaged shear wave velocity over the top 30m of the ground (V_{S30}) in the state of Alaska.

In total, we identified 704 events that meet the criteria for this type of analysis. We manually inspected these events and picked seismic wave phases as we discovered that the results strongly depend on the accuracy of the picks in the seismic waveforms. The analysis resulted in a set of estimated V_{S30} values for 254 recording sites, with the majority of them corresponding to rock sites. The validation of the V_{S30} estimates involved comparisons against data (a very limited number of sites with measured V_{S30} and average quality of the available recordings) and results from common proxy techniques such as slope-based V_{S30} estimates, local site geology and horizontal to vertical spectral ratios. Overall, the application of the receiver function method in Alaska can detect the differences between stiff soil/rock and soft soil sites with fairly good accuracy and produce a reliable set of V_{S30} estimates for the stations studied. We expect that these products will be used to improve ground motion estimates in the Alaska portion of the National Seismic Hazard Map and will provide more reliable estimates of seismic hazards and site response throughout Alaska.

Three-dimensional S-wave Velocity Model of Napa, California Obtained from Microtremor Array Measurements and Horizontal to Vertical Spectral Ratio

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We estimated a three-dimensional (3D) S-wave velocity (Vs) model of the Napa, California, U.S. using microtremor array measurements (MAM) and horizontal to vertical spectral ratio (H/V) at approximately 100 sites. MAM was collected with eight to twenty 2 Hz geophones, and the maximum receiver spacing ranged from 30 to 1500 m. Ambient noise for MAM and H/V were collected for 20-120 minutes. A spatial auto-correlation (SPAC) method calculated phase velocities from the vertical component of ambient noise. Minimum frequency of dispersion curves ranged from 1 to 10 Hz. H/V was calculated from three-component (3C) seismic ambient noise using a single 3C 2Hz geophone. The peak frequency of H/V ranged from 0.25 Hz to 10Hz. There were clear differences between valley floor and surrounding hills both dispersion curves and H/V. In the H/V spectra, there is a clear peak of H/V at a frequency of 0.3 Hz in the valley floor sites whereas there is no clear H/V peak below 1 Hz in the hill sites. Joint inversion of a dispersion curve and H/V spectrum estimated Vs profiles to 30 m to 1000 m depth. There is a large difference in resultant Vs profiles. Depth to a shallow engineering bedrock with Vs of 760 m/s is 300 m and 30 m at typical valley floor sites and hill sites respectively. It indicates that the velocity model changed considerably along the Soda Creek Fault. The result of inversion and geological model implies that the low frequency peak of 0.3 Hz at the valley floor site is mainly due to a deep bedrock with Vs more than 2500 m/s at approximately 1000 m depth. We compiled all Vs profiles together with the 3D Vs model based on geological information and estimated a preliminary 3D Vs model to a depth of 1000 meters. The VS30 obtained from the MAM ranged between 200 m/s and 970 m/s. Clear H/V peak frequencies of 0.25 to 0.4 Hz were consistent in the valley floor. The depth to the bedrock with Vs of 760 m/s ranged between almost surface to greater than 300 m.

What Are the Primary Site Response Parameters and Proxies?

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Many parameters and proxies have been used to characterize or quantify site response. However, the task of identifying the primary parameters and proxies is ongoing. For example, site response is quantified by the soil-to-rock Fourier spectral ratio (SSR) or borehole transfer function (TF) in seismology, but by ratio of response spectra (RRS) in engineering. To evaluate potential primary site-response parameters and proxies, we derived empirical and theoretical SSRs and RRSs from the weak (PGA≤0.05g) and strong (PGA>0.05g) ground motions at 21 borehole arrays in the United States and Japan. The theoretical analyses consisted of 1D site-response analyses using the shear-wave velocity profiles and other parameters at these borehole arrays. Our results show that there are two parameter pairs of primary importance: the fundamental-mode (i.e., base mode) frequency (f_0) and its associated amplification (A_0), and peak-mode frequency (f_p) and its associated amplification (A_p) on the empirical and theoretical SSRs and RRSs. Our results also show that the fundamental modes are the dominant mode on RRS at most sites. Furthermore, our results show clear nonlinear characteristics: decreases of the fundamental mode frequency and higher mode amplifications with increase of PGA. These characteristics effect RRSs such that the fundamental mode becomes the dominant mode, particularly for larger ground motions, and thus f_0 and A_0 are the primary site response parameters for engineering considerations. We also determined several proxies from the site-specific shear-wave velocity profiles, including Vs30, average sediment shear-wave velocity ($V_{s,a}$) and thickness (Z_b), bedrock shear-wave velocity (V_b) and ratio of V_b to ($V_{s,a}$) (R_{bs}). We compared these proxies with the fundamental mode parameters and showed that Z_b and R_{bs} are the best pair of proxies with the highest correlation coefficients. The comparisons also demonstrate that no single proxy is sufficient to parameterize both f_0 and A_0.

How Well Can We Predict Earthquake Site Response So Far? Machine Learning vs. Physics-based Modeling

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In site response assessments, observation-based site-specific approaches requiring a target-reference recording pair or a recording network cannot be implemented at many sites of interest. Thus, various estimation techniques have to be utilized. How effective are these techniques in predicting site-specific site responses (average over many earthquakes)? To address this question, we conduct a systematic comparison using a large dataset which consists of detailed site metadata and Fourier outcrop linear site responses based on observations at 1725 K-NET and KiK-net sites. We first develop classic regression and machine learning (i.e., random forest) amplification models on a training dataset (1580 sites). Then we test and compare their predictive powers at 145 independent testing sites with those of the one-dimensional (1D) ground response analysis (GRA) and the empirical correction to the horizontal-to-vertical spectral ratio (eHVSR) of earthquakes (c-HVSR). The standard deviation of residuals between observations and predictions is used as the benchmark.

Results show that the machine learning amplification model using a few predictor variables, surface roughness, $f_{P,HV}$, V_{S30} and $Z_{2.5}$, achieves better performance than the 1D physics-based modelling (GRA) using detailed ground structures. In addition, we propose a new machine learning amplification model using single-station eHVSR curve as a vector-valued predictor variable which is very effective in further lowering the between-site variability in the full frequency range 0.1-20 Hz. Meanwhile, GRA results can also be improved using eHVSR-consistent velocity profiles. These demonstrate the benefits of collecting on-site earthquake recordings and are particularly pertinent for cases where recording pair- or network-based empirical techniques remain a "luxury". Future endeavors could further explore the modeling of more complex site effects using machine learning techniques, single-station recordings and geotechnical measurements, which could be an alternative to the physics-based simulation.

What Is the Importance of Two- and Three-Dimensional Site Effects? An Investigation of Single-Station Earthquake Records

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In earthquake engineering, one-dimensional (1D) site response analysis dominates, while local 2D/3D models are typically required at sites where the site response is more complex. Consequently, the 1D representation of the soil column at such sites cannot take into account topographic effects, dipping layers or locally generated horizontal surface waves. The task then remains to determine whether the site response can be sufficiently precisely modelled by 1D analysis. In this study we develop a method to classify sites according to their 1D or 2D/3D nature. In this classification scheme, surface earthquake recordings are analysed and the similarity of horizontal Fourier spectra is assessed. The taxonomy is focused on capturing significant directional dependencies and inter-event variabilities indicating a more probable 2D/3D structure around the site causing the ground motion to be more variable. While no significant correlation of the 1D/3D site index with environmental parameters and site proxies seems to exist, a reduction in the within-site (single-station) variability is found. The reduction is largest (up to 20%) for purely 1D sites.

The taxonomy system was developed based on surface stations of the KiK-net network in Japan since this network offers a substantial amount of additional information, but it can also be applied to any (non-downhole array) site.

Multidimensional Site Effects at the Treasure Island Downhole Array Using Seismo-VLAB and a Site-specific 3D Model

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Over the past decade, numerous studies have examined ground motions recorded at borehole array sites and found that, on average, more than 50% of sites are poorly modeled using one-dimensional (1D) ground response analyses (GRAs). These discrepancies have been generally attributed to limitations of conventional 1D site assumptions, which disregard complex wave propagation effects resulting from laterally variable subsurface conditions present at most sites. Many studies have thus attempted to perform two- and three-dimensional (2D and 3D, respectively) GRAs. While these studies have provided useful insights, the vast majority have modeled spatial variability using stochastic spatially correlated random fields, have been limited to idealized single-layer profiles, have performed theoretical assessments without validation against actual ground motion observations and/or have been scaled down due to the computational demands of existing 2D/3D finite element software. Indeed, the lack of realistic site-specific 2D/3D subsurface models needed for multi-dimensional GRAs and the daunting computational costs of current software are fundamental limitations that hinder improved modeling of site effects in engineering practice. In this study, we aim to address both of these challenges by utilizing a framework called the 'H/V geostatistical approach' to develop large-scale, site-specific, 3D shear wave velocity (Vs) models and a new, open-source, finite element software called 'Seismo-VLAB' to optimize large-scale 2D/3D finite element analyses. The investigations are performed at the Treasure Island Downhole Array and involve 2D GRAs using cross-sections across different azimuths and lateral extents, as well as 3D GRAs using different incorporated areas. By comparing the site response predictions relative to recorded earthquake motions in the borehole array, we investigate the lateral area influencing site response and show that the site-specific 3D Vs model is capable of replicating wave scattering and more complex wave propagation phenomena observed in the recorded ground motions at the site.

Characterization of Non-ergodic Site Effects at Selected Hard-rock Sites in Western Canada

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Common ground-motion models (GMMs) are usually referenced to a moderate-stiffness rock site condition (V_{S30} =760 m/s) (time averaged shear-wave velocity in the top 30 m). However, many of the critical structures in British Columbia (B.C.) are located on hard-rock site conditions (i.e. V_{S30} of 1500 -2800 m/s). Therefore, the seismic hazard results based on moderate rock site condition should be adjusted accordingly. Generic hard-rock correction (HRC) factors (i.e. hard-to-moderate rock amplification ratios) from the literature show large amount of variability at high frequencies with amplification or de-amplification of up to a factor of 2 to 3 being common.

We propose an alternative approach for characterizing the HRC factors by estimating the non-ergodic site response at selected facilities located on hard-rock with site-specific recordings. The scope of the work includes: 1) compilation of an empirical ground-motion database for rock seismograph sites in B.C.; 2) development of regionally-calibrated hard-rock GMMs; 3) site-specific instrumental deployments at selected facilities and 4) derivation of non-ergodic site response and hard-rock adjusted hazard curves using the site-specific ground motion data.

Using the proposed approach, we derived the non-ergodic HRC factors at the locations of two installed seismographic stations at a selected facility located on hard-rock. The non-ergodic approach reduced the uncertainty in seismic hazard analysis by removing the site-to-site variability component of GMMs and including the epistemic uncertainty of the HRC factors. The non-ergodic HRC factors can differ significantly from the generic correction factors obtained from typical ground response analysis (GRA). Using site-specific hard-rock V_S profiles in GRA is unable to predict the non-ergodic HRC factors, implying that contributing factors other than the impedance effects (e.g. near-surface high frequency attenuation, topographic effects) may control the HRC factors.

Site Characterization of Seismic Stations in Metropolitan Lima, Peru

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The city of Lima is located on the central-western side of South America in a high seismic activity zone due to the subduction of tectonic plates. Regarding the geotechnical characteristics, the metropolitan area is mainly covered by stiff alluvial deposits originated by the erosional processes of three main rivers. Softer eolian and marine materials can also be found on the outskirts of the city. Given this heterogeneity, the Japan Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) has been implementing the CISMID's Accelerometer Network (REDACIS) by the installation of several acceleration sensors in the diverse soil deposits comprising Metropolitan Lima. Currently, the number of seismic stations is 36 whose signals are obtained in near-real time, which allows the implementation of reports and the dissemination of the data via CISMID's webpage.

With the objective of identifying dominant periods during strong motions, seismic records were compiled within the period 2011-2021. Then, by means of the methodology proposed in Hassani and Atkinson (2016), which involves the calculation of response spectra and the definition of thresholds from the statistical analysis of records, horizontal-to-vertical (H/V) spectral ratios were computed. In addition, field surveys, such as the Multichannel Analysis of Surface Waves (MASW) and single point microtremor measurements, were carried out for 30 stations, to obtain values of Vs30 and peak periods from ambient vibrations, respectively. Results show that stiff alluvial deposits are characterized by flat H/V spectral shapes and high values of Vs30, in the vicinity of 700 m/s. On the other hand, softer materials, with Vs30 values within the range of 300-400 m/s, are characterized by sharp spectral peaks in the intermediate-to-long period range. This might a consequence of the joint influence of the surficial materials and the considerable impedance contrast in the deeper part of the soil substructure.

Reducing the Epistemic Uncertainty in Ground Motion Prediction Equations by Incorporating Site Fundamental Frequency Using Japanese Stations in NGA-West2 Database

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The local site effect in ground motion prediction equations (GMPEs) is usually addressed by time-averaged shear wave velocity for upper 30 m (VS30) and / or depth to 1.0 km/s shear-wave velocity isosurface (Z1.0). However, VS30 does not incorporate the effect of deeper layers, and Z1.0 is usually inferred. Previous research shows that site fundamental frequency can be a useful variable for improving the performance of GMPEs. This study aims to incorporate site fundamental frequency in GMPEs for the Japanese stations in NGA-West2 database. First, previously developed automated methodologies are utilized to obtain two predictor variables (maximum-likelihood estimate of site fundamental frequency and its corresponding amplitude) for each station using the Horizontal-to-Vertical Spectral Ratio (HVSR) of ground motion records. Second, residual analysis is performed to compute site term residuals using an NGA-West2 GMPE. Third, a model is developed based on the relationship between site term residual and the HVSR-based predictor variables. Utilizing this model in the NGA-West2 GMPE results in better prediction of ground motions by reducing the epistemic uncertainty. The standard deviation of site term residuals, so-called site-to-site variability (ϕ S2S), is reduced about 15% on average. As a result, the total uncertainty in the GMPE is reduced by 3% on average indicating the effectiveness of HVSR-based model.

A Practical Approach for Accounting for Vs Spatial Variability Using 1D Site Response Analyses

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One-dimensional site response analysis (1D SRA) remains the state of practice for estimating site-specific seismic response. Various studies have shown discrepancies between 1D SRA predictions and ground-motion recordings (e.g., Kaklamanos et al. 2013) that were attributed to errors in the shear-wave velocity (V_S) profiles and intrinsic limitations of 1D SRAs. While it is recognized that practice should move to 2D and 3D SRAs, their implementation is hindered by the level of detail and computational demand that these analyses require. Therefore, developing 1D SRA approaches for estimating a more appropriate seismic response is critical while transitioning to more advanced numerical methodologies.

In this study, linear elastic 1D SRAs are conducted with V_S randomization to account for V_S spatial variability effects on amplification factors (AFs). A numerical evaluation with 1D SRAs conducted on randomized V_S profiles, generated using the Toro model (1995) and $\text{sigma}_{\ln V_S} = 0.25$, indicates that the 84th percentile AF approximates well the median AF estimated from more realistic 2D SRAs at the site's resonant frequency. Ground-motion recordings from around 500 downhole array sites in Japan and the U.S. are used to substantiate the numerical findings. The sites are first grouped according to the level of compliance to 1D SRA assumptions, and empirical AFs are estimated and compared against 1D SRA-based median and 84th percentile AFs. Preliminary results from this evaluation support the overall benefit of using higher percentile AFs, particularly for sites that are not expected to undergo effects from complex geological features beyond the V_S spatial variability. Estimates of the method's bias for 1D SRAs conducted with two commonly used damping relations are presented and discussed.

Linear Site Response of Soft Peaty Organic Soil Sites in California's Bay-Delta Region

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Levees founded on peaty organic soils in the Sacramento-San Joaquin Delta region of California are vital infrastructure that supply much of the State with fresh drinking water and protect Delta islands from inundation. Therefore, the damage or breach of a levee as a result of an earthquake has the potential for catastrophic impacts. These peaty-organic soils have characteristic V_{S30} values typically in the range of 100 to 200 m/s, which is softer than the lower limit for NGA-West2 ergodic site response models. In this study, we use a large database of recordings from 33 instrumented sites located within the Delta to evaluate the linear site response using non-ergodic site response procedures. Based on these site-specific results, a regional linear site response model is developed that is conditioned on 30-m time-averaged shear wave velocity, V_{S30}. Relative to a current (NGA-West2) ergodic model, we find evidence of amplification being over predicted at short periods with lower V_{S30}-scaling at low V_{S30}. For long periods, we find prior models to under-predict the site response, with no apparent V_{S30}-scaling. We are further examining the relationship between site response and other predictor variables (such as peat thickness and site fundamental period) to improve ground motion predictions at sites with peaty deposits in the Delta region. When coupled with an improved regional path effect model (described separately), these local site response models hold the potential to significantly improve ground motion predictions and reduce epistemic uncertainty in this vital region.

Nonlinearity of the Vertical Ground Motion Component

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The importance of vertical ground motions for design continues to gain recognition, as more evidence shows that vertical ground motions can significantly exceed their horizontal counterparts on very soft soils, at short source-site distances and at short spectral periods. Assuming that the vertical component is largely comprised of compressional P-waves, new approaches and models are required to constrain the expected linear and nonlinear site response of the vertical component.

In this study, we combine empirical analysis with laboratory experiments, to study and define the nonlinear behavior of the vertical component. We use 27 Kik-net stations to analyze nonlinearity of dry sandy deposits, comparing the full vertical component with the P-wave window, to help define the partial contribution of P-waves to the entire vertical component. We develop modulus degradation and damping (MRD) curves for the case of uncoupled and coupled shear-compression response. In addition, we compare the empirical MRD curves with experimental MRD curves, describing the response of sandy soil to cyclic compressional loading under Ko conditions. We show that vertical ground motions are less nonlinear than their horizontal counterpart, for the same incoming ground motion. We also show that pure P-waves are less nonlinear than the full vertical motion, suggesting that the vertical component is comprised of a combination of P and SV waves, thus implying that vertical site-response analysis should include both shear and compression-related properties and procedures.

Site Response Characterization in Seismic Hazard Analysis

Poster Session · Friday 22 April · Conveners: Behzad Hassani, BC Hydro (behzad.hassani@bchydro.com); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Sean K. Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Gail M. Atkinson, Western University (gmatkinson@aol.com); Anna Kaiser, GNS Science (a.kaiser@gns.cri.nz); Marta Pischiutta, Istituto Nazionale di Geofisica e Vulcanologia (marta.pischiutta@ingv.it); Jonathan P. Stewart, University of California Los Angeles (jstewart@seas.ucla.edu); Chuanbin Zhu, GFZ Potsdam (chuanbin@gfz-potsdam.de)

Analysis of Ground Motions Using Recorded Earthquakes and Ambient Vibrations in the Matanuska-Susitna Valley and Eagle River, Alaska

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The Matanuska-Susitna (MatSu) Valley and Eagle River areas located northward to Anchorage suffered extensively during the 2018 Anchorage earthquake of M7.1. In addition to widespread ground failures and soil-liquefaction at several places, schools and residential buildings were damaged significantly in both areas during this earthquake. However, due to the lack of recorded strong-motion data, the characteristics of the ground motions could not be well correlated with the observed damage. Moreover, with the rapid growth in population in both areas during the last two decades and their proximities to several seismically active faults, the earthquake hazard has become a critical issue. To assess the spatial variations of ground response during strong shaking and its relation to the subsurface geological formations, three strong-motion sensors (Etna2 of Kinemetrics) were installed in the MatSu Valley and four in the nearby Eagle River area in collaboration with Alaska Earthquake Center. The network has been operational since February 2021 and has already recorded several earthquakes of magnitude from M4.5 to M6.1. Preliminary analyses have been carried out to obtain the Horizontal to Vertical spectral ratio of the S-wave portion of these recorded earthquakes (eHVR) and the ambient vibrations (mHVR) in a frequency range of 0.5-30 Hz. The relatively high fundamental frequencies (f_0) of the HVR agree well with the shallow engineering bedrock at each site in these areas. In addition to the HVR studies, the active source Multichannel Analysis of Surface Wave (MASW) has also been carried out using a 24-channel vertical geophone (4.5 Hz) system with 7 ft geophone spacing at these sites. The joint inversion of the HVR spectrum and the surface wave phase velocities from the MASW have been performed to delineate the shallow subsurface structure at each location and estimate the time-averaged 30 m shear wave velocity (Vs30) values. The results indicate that the estimated Vs30 data correlate well with the general geological trend of these two areas.

Energy Partitions Among Elastic Waves for Dynamic Surface Loads in Layered Media

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A mechanical state of an elastic vibrating medium can be described in terms of its normal modes. The seismic energy associated with the Green's function (GF) is equitably distributed in all modes and states (different types of elastic waves). That is, they fulfill the principle of Energy Equipartition. The theory asserts that within a diffuse field, the elastic regime and the directional energy densities are composed by the contribution of all modes, which is linked to the GF. The energy partition values for the P-SV, SH and Rayleigh waves in a half-space for surface loads correspond to vertical and horizontal forces: 1) vertical displacements at the source generated by a vertical point force, 2) a horizontal point force generates horizontal displacements at the source. Both cases have been computed for an elastic half-space. The results obtained show that the energy is distributed in different waves. In the first case, the P waves carry 8% of energy, SV waves 26% and surface Rayleigh waves 66%. In the second case, SH waves carry most of the seismic energy with 60%; Rayleigh surface waves 18%; SV waves 16% and P waves 6%. These classical results are valid only for a half-space. In nature, the phenomenon is more complex. The first step is to extend these observations to layered media. This work shows the modal distribution of seismic energy for a diffuse field in stratified media obtained from the imaginary parts of the GF of the displacement field when the source and receiver coincide. These results allow us to analyze the multimodal effects that make it difficult to select particular Rayleigh- and Love-wave modes in empirical dispersion diagrams. Furthermore, this analysis allows for an explicit relationship between the dispersion curves and the Horizontal-to-Vertical Spectral Ratios under the diffuse field theory.

Evaluation of Kinematic Soil-structure Interaction Effects for Vertical Motions at Multiple Instrumented Sites with Large and Deeply Embedded Foundations

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The earthquake motion experienced by a building can be affected by the soil-structure interaction (SSI) effects. As a result, motion at the foundation level of a building (FM) can deviate from free-field motion (FFM). Kinematic and inertial SSI effects are two mechanisms that simultaneously cause this deviation, among which kinematic SSI is a result of stiff foundation elements. The kinematic SSI effects can be quantified using procedures that are semi-empirical and were calibrated using earthquake motion databases of multi-story buildings in different parts of California. In the design guidelines such as ASCE/SEI 41-17 kinematic SSI is considered by calculating the Ratio of Response Spectra (RRS) between FM and FFM. However, the current simplified methods are limited only to horizontal translational motions for buildings with regular foundation width and embedment depth, and there is a lack of any recommendations for vertical translational motions.

This study presents empirical vertical RRSs based on recorded data at five well-instrumented nuclear facilities in Japan. Recorded data at multiple buildings were used to calculate RRSs for vertical motions from multiple earthquake recordings to evaluate the extent of kinematic SSI in buildings with large and deeply embedded foundations when subjected to vertical earthquake motions. Then a comparison between empirical vertical and code-based horizontal RRSs is made illustrating the need to establish a code-based procedure for vertical RRS. Also, a comparison between empirical vertical and empirical horizontal RRSs is conducted. The overall results of comparisons illustrate that code-based horizontal RRSs tend to overestimate the foundation vertical translational motions. Furthermore, the extent of the overestimation is maximum near the range of fundamental frequency of structures that can be attributed to the inertial SSI effects besides kinematic effects. In future steps of this study, the results will be used to develop a set of empirical equations for estimating vertical RRS which provides a basis for developing new recommendations on kinematic SSI modeling.

Evaluation of Modified Simplified Equations for Estimating Kinematic Soil-structure Interaction Effects in Buildings With Large Footprints and Embedment Depths: A Finite Element Approach

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Current design guidelines include a simplified procedure to estimate the kinematic Soil-Structure-Interaction (SSI) effects which is mainly responsible for variations between foundation-level and free-field ground motions. Although insightful, available code-based procedures were developed for regular size buildings with footprint size less than 260ft and embedment depth shallower than 20ft. Therefore, using such equations for design of buildings with large foundations and embedment depths, similar to those found in nuclear facilities, can be highly unrealistic. Using a dataset of earthquake motions recorded at five instrumented nuclear sites in Japan, an empirical study has been recently completed at UNR to modify the current simplified code-based formulations to account for kinematic SSI effects in buildings with large footprints and embedment depths. However, even the modified simplified equations may not be used for sites with characteristics different than those included in the dataset imposing some restriction in the applications.

The Finite Element Method (FEM) is an efficient numerical tool to take the kinematic SSI effects into account. In this study, a well-instrumented site located in Japan is selected where a building with large footprint and embedment depth was subjected to several seismic events as a case study. A three-dimensional (3D) Nonlinear (NL) SSI analysis in the time-domain code LS-DYNA is benchmarked against the actual recordings for a wide range of earthquake intensities. Results from the NL FEM analyses, the simplified code-based formulations, and the modified simplified equations are compared with the actual recordings. It is demonstrated that the FEM is an efficient tool to evaluate the kinematic SSI effects for design purposes.

Future Directions of the COSMOS Site Characterization Committee

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The fundamental aim of site characterization is to develop comprehensive subsurface geologic and geotechnical models. Such models are of critical importance to multiple communities and are employed for a wide range of purposes including seismic hazard assessment, design and assessment of critical infrastructure such as nuclear facilities, levees, dams and linear alignments for pipelines. The diversity of alternative approaches for site characterization brings the need for some standards or guidelines for the potential users. The International Guidelines for Site Characterization project of Consortium of Organizations for Strong Motion Observation Systems (COSMOS) started in 2015 through the consensus of the international site characterization and site response research community. Since then, the corresponding International Facilitation Committee has been working towards developing international guidelines for applying non-invasive geophysical techniques to characterize seismic site conditions. In this talk, the presenters, which lead the project as of Fall 2021, will introduce their vision, mission and plans for the near future with particular focus on multi-disciplinary teamwork, integration of research and practicing community, inclusion of advanced technologies and search for sustainable international funding.

Implementing Non-ergodic Ground-motion Models in Probabilistic Seismic Hazard Programs

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The move from ergodic to non-ergodic ground-motion models (GMMs) has led to concern about implementation of non-ergodic GMMs into PSHA software. The median ground motion will depend on the coordinates of the site and the closest point on the rupture plane to the site in addition to the closest distance. We describe one approach for implementing non-ergodic GMMs into PSHA in which the non-ergodic GMM is modeled as an adjustment term to an ergodic GMM. For a given site, the combined source, path, and site non-ergodic terms are computed for each source location outside the PSHA pro-

gram. The epistemic uncertainty is spatially correlated and is modeled by 100 realizations (maps) of the non-ergodic terms which are logic tree branches for the non-ergodic term. The PSHA program is modified to pass the coordinates of each source to the GMM subroutine which adds the source-specific total non-ergodic term to the log median ground motion.

This method has been implemented in HAZ45 (github/Abrahamson.com) and is being tested in OpenQuake. There is an issue about the increased calculation times for non-ergodic PSHA due to using 100 GMM maps compared to a small number of ergodic GMMs typically considered. For fault sources, this calculation time issue has been addressed in HAZ45 using polynomial chaos to propagate the epistemic uncertainty in the non-ergodic terms which leads to calculation times similar to using 2 GMMs in the traditional approach while maintaining accurate epistemic fractiles. For areal sources, there is an even greater increase in run time because the common approach of combines the rates of different parts of the source zone that are at the same distance and computing marginal hazard only once for each magnitude-distance scenario cannot be used because the non-ergodic terms are different at each source location. We developed a method to approximate an arbitrary distribution of the non-ergodic terms from parts of the zone at the same distance which reduces the run times by about a factor of 50 compared to direct sampling over the zone.

Machine Learning-based Models to Predict Ground Motion Intensity in South Korea

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South Korea was recently struck by two earthquakes with local magnitudes (M_L) of 5.8 and 5.4, which were recorded as the first and second-largest earthquakes in the Korean Peninsula. These two earthquakes are attracting attention for the necessity of seismic hazard evaluations in Korea. Some ground motion prediction models (GMPMs) have been developed in South Korea. Emolo et al. (2015) used 11,129 ground motions recorded during 222 earthquakes between 2007 and 2012 to make the ground motion prediction equation (GMPE). Jeong and Lee (2018) made a GMPE using 115,000 synthetic ground motions generated by the ground motion model developed on the seismic records from 11 earthquakes between 2003 and 2016.

In this study, we developed GMPMs to estimate 5% damped pseudo-spectral accelerations (PSAs) at 27 periods ranging from 0.01 to 10 s based on three machine learning techniques: Random Forest (RF) and Gradient Boosting (GB) with 500 trees, and Artificial Neural Network (ANN) that consists of two hidden layers with 31 and 51 nodes. We used 1,189 ground motions recorded at 50 surface stations in South Korea. We considered five independent variables: M_L, epicentral distance (R_{epi}), average shear wave velocity of the upper 30 m (V_{S30}), focal depth and slope angle. The prediction performances of three machine learning-based models were compared with a classical regression-based model (Emolo et al., 2015). Among the four models, the GB-based model showed the best performance with the smallest errors on the unseen data. To compute variable importance, we used Mean Decrease in Impurity function. It turned out that the R_{epi} and M_L were the most influential for periods ranging from 0.01 to 0.1 s and periods longer than 0.2 s, respectively. We also applied the GB-based model to recent earthquakes and the estimated PSAs were in good agreement with the records. To enable to implement in seismic hazard assessments, we developed an executable version of the trained GB-based model.

Minimizing Geophysical Site Characterization Procedures to Estimate Vs30 Through the Use of Vr40

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We develop minimal site characterization procedures (MSCP) for estimating V_{S30}, the time-averaged shear wave velocity of the upper 30 m from the ground surface. V_{S30} is typically calculated from shear-wave velocity (V_S) profiles, which are determined by expensive and invasive borehole-based methods or by noninvasive surface-wave methods (SWMs). These conventional SWMs involve time-consuming iterative inversion calculations, in addition to field acquisition procedures requiring large multi-channel arrays and multiple methods using active and/or passive sources. Brown *et al.* (2000) and Yong *et al.* (2017) have established linear empirical relations between V_{S30} and the Rayleigh-wave phase velocity at the 40 m wavelength (V_{R40}). Utilizing data acquired by the ARRA project (Yong *et al.*, 2013), we test a minimal procedure for estimating V_{S30} by measuring V_{R40} from standalone passive or active SWMs. We measure V_{R40} utilizing the fundamental-mode dispersion curve, typically derived from the V_R spectrum of various SWMs. In addition to measurements of V_{R40}, the site characterization approach provides microtremor recordings for estimations of the dominant site frequency (f_d) using the horizontal-to-vertical spectral ratio (mHVSR) method. While mHVSR-based f_d analyses are ongoing, comparison of our V_{R40}-based V_{S30}, acquired from theoretical tests of our MSCP, and conventional V_S profile-based V_{S30} show good agreement (average difference less than 3.5%). Field tests of our MSCP—at sites with existing V_S profile-based V_{S30}—are necessary for validation of the robustness of the approach. Pacific Gas & Electric-operated dam sites are sites of interest and provide test cases that will contribute to verifying the viability of the MSCP. We seek not to eliminate the need for V_S profiles necessary for detailed ground response analyses, but instead to design a method to expedite estimation of V_{S30} at seismic stations where currently no measured shear-wave velocity information exists.

Modeling of the Surface-to-depth Spectral Amplification in 3D Media

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High-frequency (>1Hz) surface-to-depth spectral amplification is one of the key features of site response characterization relating ground motion at depth and on the surface. This site-specific transfer function can be retrieved for sites with borehole monitoring arrays by computing surface-to-borehole spectral ratios for multiple records of regional earthquakes (i.e. empirical S/B ratios). Nevertheless, modelling and predictions are challenging due to limited knowledge of the heterogeneous near-surface velocity structure, and due to complexity of the impeding high-frequency near-surface wave-field. Moreover, modelling of simple SH-wave depth-to-surface transfer function in 1D medium produces distinctive narrow spectral peaks of high amplitudes unobserved in empirical data. Recently, a novel stochastic model has been introduced for 1D media providing a good fit to empirical data in the broad frequency range for sites with 1D resonance effects. In this contribution, we introduce a strategy for modelling the surface-to-depth amplification in 3D media using a finite-difference method. The finite-difference numerical modelling is done for fine 3D subsurface structures with smoothed boundaries and random heterogeneities, which results in surface-to-depth amplification functions without unrealistic spectral peaks. The final comparison of our prediction of amplification to real data is made for KiK-net stations with empirical S/B ratios indicating the presence of either 1D or complex site effects characterizing a particular site.

S-wave Site Amplification Factors From Observed Ground Motions in Japan: Validation of Delineated Velocity Structures and Proposal for Empirical Correction

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We first derived site amplification factors (SAFs) from the observed strong motions by the Japanese nationwide networks, namely, K-NET and KiK-net of National Institute of Earthquake Research and Disaster Resilience (NIED) and Instrumental Seismic Intensity Network of Japan Meteorological Agency by using the so-called generalized spectral inversion technique (GIT). We can use these SAFs for strong motion prediction at these observation sites, however, we need at least observed weak motion or microtremor data to quantify SAF at an arbitrary site. If we know a velocity structure, we can use one-dimensional theoretical transfer functions (TTF) to estimate SAF. The precision of the TTF depends on the precision of the velocity model. We tested the capability of the current velocity models in Japan whether they can reproduce or not the observed SAFs based on the unified velocity model of NIED for the Kanto and Tokai regions where the shallower- and deeper-parts of the velocity structure are combined (Senna et al, 2019). The observed site amplification factors were obtained by GIT relative to the reference spectra extracted as the outcrop motions on the seismological bedrock (Nakano et al., 2015). To be consistent with these observed SAFs, the TTFs on the surface are calculated relative to the outcrop motions on the seismological bedrock. We found that at about one-half of the sites the calculated TTFs show acceptable fit to the observed SAFs, however, the TTFs tend to underestimate the observed SAFs in general. Therefore, we propose a simple, empirical method to fill the gap between the observed SAFs and the calculated TTFs based on the frequency and amplitude modification ratios. Once we obtain these modification ratios at 546 observed sites, we can interpolate them in space to obtain the modification ratios at an arbitrary point. Validation examples show that our proposed method effectively predict better site amplifications than the direct substitute of TTFs at a site without observed data.

Shear Wave Velocity Profile Using Seismic Motion and Ambient Noise HVSR at KMA Seismic Observatory Stations

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Horizontal-to-Vertical Spectral Ratio (HVSR) is used to obtain the site natural frequency which corresponds to the peak frequency of HVSR. Recently, using the diffusion theory, HVSR is also used to estimate a shear wave velocity (VS) profile (García-Jerez et al., 2016). The VS profile provides more detailed subsurface information so that an advanced analysis (e.g., site response analysis) can be done. The present study aimed to determine VS profiles of national seismic stations operated by Korea Meteorological Administration (KMA) using HVSR. We used both ambient noise and seismic waves for HVSR estimation, which represent surface wave and body wave, respectively. The inversion of HVSR for VS profile using surface wave has been studied priori, but not many studies compared the VS profile from HVSR of body wave to one from surface wave. We collected surface records including 24 hours of ambient noise and seismic waves from five earthquakes (Pohang, Gyeongju, Ulsan, Taean and Jeju) with a magnitude of 4.9 or higher for 47 KMA seismic stations. Ambient noise HVSR was calculated by dividing the 24 hours records into 15 minutes and averaging a total of 96 data, and the body wave part (P and S-waves) of seismic wave HVSR was calculated by setting the P-wave arrival and S-wave end time through STA/LTA technique. This study compared VS profiles inverted from ambient noise and seismic wave HVSR, and the reliability of each data set was identified by comparing to the existing boring and VS profiles.

Uncertainty Quantification of Conditioned Simulation of Ground Motions

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Recently we developed a methodology to generate ground motion time series at target sites where there is no installed recording instrument. We used Gaussian Process Regression (GPR) model to conditionally simulate ground motion time series. This GPR model estimates the motions at the target sites given a set of observed ground motions and site conditions of the stations. The focus of the current study is the quantification of the uncertainty and validity of these predicted motions. We introduce a methodology to generate random realizations of ground motions using the trained GPR model and an established inter-frequency correlation model. We utilized this methodology for the 2019 M7.1 Ridgecrest Earthquake Sequence recorded by the Community Seismic Network (CSN) and California Geological Survey (CGS). In addition, we investigated the sensitivity of the estimated motions' accuracy and uncertainty to various parameters such as density of the observations surrounding each target site and uncertainty of the estimated local site condition. Moreover, we studied the improvement of the GPR model's performance for estimation of the ground motions at CGS stations by feeding more observed motions from CSN to the model for the Ridgecrest earthquake dataset. The results illustrate that in general the uncertainty of the generated time series is lower for longer periods than that for shorter periods. Also, it is shown that the density of the observations surrounding each target site plays a key role in the accuracy and the uncertainty of the estimated motions.

Vs30 Site Characterization in the Hayward Hills, San Leandro, California, Using Multiple Methods

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We evaluated Vs_{30} near a strong-motion recording site (SLR; 37.718014, -122.096655) at Lake Chabot Regional Park in San Leandro, California, using data recorded on a 120-m-long linear array of 60 nodal seismometers with 2 m spacing and co-located seismic sources, generated with a hammer and plate combination. Compressional and Rayleigh waves were generated by vertically striking an aluminum plate, and shear- and Love waves were generated by horizontally striking an aluminum block tethered to the ground. Two-dimensional shear-wave velocity (*Vs*) models were developed using refraction tomography on S waves and the Multi-Channel Analysis of Surface Waves (MASW) method on Rayleigh and Love waves. Vs_{30} was evaluated along the entire length of the seismic profile, and we find it ranges from 623 to 731 m/s. For the seismometer nearest to the strong-motion recording site, Vs_{30} estimates are 680 m/s from S-wave refraction tomography, 669 m/s from Rayleigh-wave MASW and 641 m/s from Love-wave MASW. All measurements indicate that the site has a NEHRP classification of Class C (soft rock), consistent with expectations of local lithology (Jurassic shale, sandstones, conglomerates and limestones). We also developed *Vp, Vp/Vs* ratio and Poisson's ratio models along the seismic profile. *Vp* ranges from 500 m/s to 4500 m/s, with groundwater (1500 m/s) inferred at about 13 m depth. *Vs* along the profile ranges from 300 m/s to 1500 m/s, *Vp/Vs* ratios range from about 2.0 to 2.5 and Poisson's ratios range from 0.30 to 0.42. Rayleigh wave and topographic tomography models are similar; however, Love wave MASW tomographic models differ.

Vs30 Site Characterization Near the Strong-motion Recording Site at Fremont Central Park, California, Using S-wave Refraction Tomography and Multichannel Analysis of Surface Waves Methods

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To better understand earthquake-generated ground shaking at Central Park in Fremont, California, we evaluated VS30, the time-averaged shear-wave velocity in the upper 30 m of the subsurface, near a network strong-motion seismometer (CE.57213) located inside the Fremont Police Department, ~100 m from the mapped trace of the Hayward Fault. We acquired 2D active-source seismic data at the site and recorded both body and surface waves along a 118-m-long linear array of three-component nodal seismometers. We generated P- and S-waves using a sledgehammer to strike an aluminum block both vertically and horizontally, respectively, every 2 m along the array, coincident with each nodal seismometer. We used refraction tomography to develop 2D tomographic models of VP, VS, VP/VS ratios and Poisson's ratios along the seismic profile, and we use the Multichannel Analysis of Surface Waves (MASW) method to evaluate Rayleigh and Love waves to develop additional 2D Vs models. From the tomographic Vs model, we calculated VS30 at the site nearest the strong-motion seismometer. Our tomography model shows that VS30 ranges from approximately 472 m/s to more than 670 m/s along the profile, with a VS30 value of 673 m/s nearest the strong-motion seismometer. These VS30 values suggest the site is a NEHRP Class C (dense soil and soft rock) site. The MASW models of Vs will also be compared to VS30 values calculated from each method.

Within-site Variability in Earthquake Site Response

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The within-site variability in site response is the randomness in site response at a given site from different earthquakes and is treated as aleatory variability in current seismic hazard/risk analyses. In this study, we investigate the single-station variability in linear site response at K-NET and KiK-net stations in Japan using a large number of earthquake recordings. We found that the standard deviation of the horizontal-to-vertical Fourier spectral ratio at individual sites, i.e., single-station HVSR sigma $\sigma_{HV,s}$, approximates the within-site variability in site response quantified using surface-to-borehole spectral ratios (SBSR, for oscillator frequencies higher than the site fundamental frequency) or empirical ground-motion models (GMMs). Based on this finding, we then utilize the single-station HVSR sigma as a convenient tool to study the site-response variability at 697 KiK-net and 1169 K-NET sites. Our results show that at certain frequencies, stiff, rough and shallow sites, as well as small and local events tend to have a higher $\sigma_{HV,s}$. However, when being averaged over different sites, the single-station HVSR sigma, i.e., σ_{HV}, increases gradually with decreasing frequency. In the frequency range of 0.25-25 Hz, σ_{HV} is centred at 0.23-0.43 in ln scales (a linear scale factor of 1.26-1.54) with one standard deviation of less than 0.1. σ_{HV} is quite stable across different tectonic regions, and we present a constant, as well as earthquake magnitude- and distance-dependent σ_{HV} models.

Structure and Seismogenesis of Subducting Slabs

Oral Session · Friday 22 April · 10:00 AM Pacific

Conveners: Yingcai Zheng, University of Houston (yzheng12@uh.edu); Neala Creasy, Colorado School of Mines (nmcreasy@mines.edu); Heidi Houston, University of Southern California (houstonh@usc.edu); Zhigang Peng, Georgia Tech (zpeng@gatech.edu); German A. Prieto, Universidad Nacional de Colombia (gaprietogo@unal.edu.co)

Deep Slab Seismicity Limited by Rate of Slab Deformation in the Transition Zone

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Deep earthquakes within subducting lithosphere (slabs) have remained enigmatic because they have many similarities to shallow earthquakes, yet frictional failure of rocks is strongly inhibited at high pressure. While there are several proposed triggering mechanisms for deep earthquakes, it is not clear where in the slab each mechanism would be viable because multiple conditions (e.g., temperature, stored elastic energy) must be met simultaneously. I will show simulations of subduction with non-linear rheology and compositionally-dependent phase transitions that exhibit strongly variable strain-rate magnitude in space and time with similarities to observed seismicity versus depth profiles. High strain-rates occur in bending regions of the slab and migrate as the slab buckles and folds at the base of the transition zone. However, in between these strongly-deforming regions the strain rate is low due to the strong temperature-dependence of viscosity and high yield strength of the slab. I argue that in addition to temperature and stress requirements of deep earthquake mechanisms, variations in strain-rate determine the spatially-variable distribution of deep earthquakes (gaps, peaks, rate of seismicity). Finally, I will describe how we are further testing this hypothesis for the mechanism of thermal shear instability, and show preliminary results for visco-elastic-plastic models of subduction.

Deep Earthquake Stress Drops and Body-wave Tomography of the Tonga Subduction Zone

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The Tonga subduction zone hosts about two-thirds of the world's deep-focused earthquakes (300-700 km) and represents the cold endmember of global subduction zones. We apply a modified spectral decomposition method to estimate the stress drops of hundreds of small to moderate intermediate-depth and deep-focused earthquakes in the Tonga slab. Our results suggest that these earthquakes have an average stress drop of 2.8 MPa and do not change significantly with magnitudes. The median stress drop appears to decrease with depth in two depth ranges: (1) from 6.6 MPa at 70 km to 2.2 MPa at 250 km and (2) 4.5 MPa at 400 km to 2.0 MPa at 600 km. Median stress drops also show spatial variations, with two anomalous high stress-drop regions (15–20 MPa) coinciding with strong local deformation where the Tonga slab bends and tears. In the Tonga double seismic zone at 120–300 km depths, the median stress drop appears smaller in the lower plane than in the upper plane, suggesting a slower rupture velocity or a higher fluid content in the lower-plane region. In addition, we use regional and global body-wave datasets to image the Tonga subduction zone to 800 km depth. Our preliminary results show that a few large deep earthquakes occurred in the high-velocity slab where it is deflected in the mantle transition zone.

Aftershock Properties of Intermediate-depth Earthquakes Beneath Japan: Implications for Rupture Mechanism

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At subduction zones, intermediate-depth earthquakes (70–350 km) occur where higher temperatures and pressures should prevent brittle failure, so some other mechanism is necessary to explain their cause. The most viable mechanisms for intermediate-depth earthquakes are dehydration embrittlement, a process in which fluids from mineral dehydration reactions reduce the normal stress, and thermal shear instability, a process in which localized heating induces slip on a melt-lubricated fault. At all depths, earthquakes have similar properties, but intermediate-depth earthquakes generate fewer aftershocks than both shallow and deep-focus earthquakes (>350 km). To investigate why intermediate-depth earthquakes have fewer aftershocks, we analyze the aftershock sequences of 14 intermediate-depth earthquakes with local magnitude $M_J \geq 5.7$ from the Japan Meteorological Agency earthquake catalog from 1 May 2003 to 31 July 2018. We observe at least one aftershock for all 14 earthquakes. We find that 7 aftershock sequences have temporal patterns similar to shallow earthquakes: the number of earthquakes increases immediately following the mainshock and exponentially decays with time. The magnitude differential ΔM between the mainshock and largest aftershock is 2–3.5, larger than the typical ΔM of ~1 for shallow earthquakes. The fraction of seismic moment F_m released in the aftershocks relative to the mainshock is 0.000007–0.073, smaller than a previously observed F_m value of ≤0.10 for shallow sequences. A large ΔM and small F_m suggests more stored energy is released in the mainshock with less available for aftershock production. The high energy release could be attributed to a fault with few barriers to prevent slip or a melt-lubricated fault.

Aftershock Distributions, Moment Tensors and Stress Evolution of the 2016 Iniskin and 2018 Anchorage Mw 7.1 Alaskan Intraslab Earthquakes

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We will present a detailed study of two Mw 7.1 intraslab intermediate-depth earthquakes that occurred in southern Alaska: the Iniskin earthquake of January 24, 2016 and the Anchorage earthquake of November 30, 2018. We relocated and recovered moment tensors for hundreds of aftershocks following both events and inverted for stress histories. The aftershock distribution of the Iniskin earthquake suggests that the rupture propagated updip along a fault dipping steeply into the Pacific Plate and terminated at a stratigraphic horizon, inferred to be either the interface or Moho of the subducting slab. In addition, four earthquakes ruptured the main fault in the preceding two years and had similar moment tensors to the mainshock. This evidence suggests that the mainshock likely reactivated a pre-existing, outer-rise fault. The Anchorage earthquake sequence is complex due to its location near the boundary of the subducting Yakutat and Pacific plates, as evidenced by the aftershock distribution. Aftershock hypocenters form two main clusters that appear to correspond to orthogonal, conjugate faults, consistent with the two nodal planes of the dominant focal mechanisms. Both geographic groups display many focal mechanisms similar to the mainshock, which could indicate simultaneous rupture on conjugate planes. The time dependence in stress ratio for the Iniskin sequence can be interpreted in terms of pore-pressure evolution within the mainshock fault zone. In particular, our observations are consistent with a dehydration-assisted transfer mechanism where fluids are produced during rupture through antigorite dehydration and raised to high pore pressures through matrix collapse and/or thermal pressurization. The Anchorage sequence exhibits a more complex stress ratio evolution that may be associated with stress adjustments within a distributed fault network or reflect a strongly heterogeneous stress field.

Duplex and Moho Earthquakes Beneath the Lesser Himalaya in India

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In this study we investigate small earthquakes occurring in the crust and lithospheric mantle beneath the Indian state of Uttarakhand. This region resides at the westernmost end of what is referred to as the 'central seismic gap', where a great (>M8) plate boundary earthquake has not occurred along the Main Himalayan Thrust (MHT) in over 500 years. While the up-dip portion of the MHT remains frictionally locked, ambient seismicity observed throughout the crust and at Moho depths provides insight into how the Himalayan arc is actively deforming and contributing to the genesis of future large earthquakes.

In the upper crust (<25 km), a dense band of NW-SE trending seismicity indicates active fault structures below the physiographic transition from the Lesser to Higher Himalaya. Most notably, a dense cluster of earthquakes in proximity to the 1999 Mw 6.5 Chamoli earthquake delineate two moderately dipping faults splaying above the MHT. With the addition of focal mechanisms, we infer these faults to be imbricate thrusts and associated with a Lesser Himalaya duplex. Such a structure is consistent with surface geological interpretations and seismological observations made elsewhere along the arc, suggesting it may play a significant role in accommodating convergence between the Indian and Eurasian plates.

In the lower crust and lithospheric mantle (30-60 km)—where it is argued that conditions are unfavorable for brittle failure to occur—we provide evidence for the existence of earthquakes taking place. Most focal mechanisms for select high-quality earthquake locations indicate normal faulting. We infer such seismicity at near-Moho depths beneath the Lesser Himalaya to largely reflect flexural bending of the Indian lithosphere. This observation challenges the notion that the strength of the lithosphere is confined to the crust and suggests that other dynamic processes (such as underplating) may be promoting brittle deformation deep beneath the Himalayas.

The Role of Subducted Fluids in the Genesis of Deep Earthquakes: Evidence From Deep Diamonds and Subduction Zone Thermal Modeling

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The role of subducted fluids in the generation of deep earthquakes (300 – 700 km) has been debated for decades. Fluids feature in the genesis of intermediate depth earthquakes (70 – 300 km) but it is often argued that fluids (i.e., water or carbonate melt) cannot be transported to sufficient depth to trigger or facilitate deep earthquakes. Silicate inclusions in sublithospheric diamonds show up to ~1.5 wt% water in the mantle transition zone [1] while metallic inclusions in sublithospheric diamonds trace serpentinized slabs from the trench to the top of the lower mantle [2]. Given this and other evidence for slab-derived fluids at transition zone depths, we investigate the ability of fluids to be carried by subducted slabs by compiling a) new subduction zone thermal models, b) slab earthquake locations within these modeled subduction zones and c) phase relations of hydrated or carbonated mantle peridotite and basaltic crust. Our results are consistent with the necessity of fluids in the generation of deep seismicity [3]. Those slabs capable of transporting water to the bottom of the transition zone (in dense hydrous magnesium silicates) or that intersect the carbonate-bearing basalt solidus to generate carbonatitic melts, produce earthquakes at transition zone depths. Conversely, virtually all slabs that do not transport water or carbonate do not generate deep earthquakes. We suggest that hydrous and/or carbonated fluids released from subducted slabs lead to fluid-triggered seismicity, fluid migration, diamond precipitation and inclusion crystallization. Deep focus earthquake hypocenters would then track the general region of deep fluid release and migration in the mantle transition zone [3].

[1] Pearson, Brenker, Nestola, Mcneill, Nasdala, Hutchison, et al. (2014). Nature, 507, 221–224. [2] Smith, Ni, Shirey, Richardson, Wang and Shahar (2021) Science Advances 7: eabe9773 [3] Shirey, Wagner, Walter, Pearson and van Keken (2021) AGU Advances: 2, e2020AV000304.

Metamorphism-facilitated Faulting in Deforming Orthopyroxene: Implications for Global Intermediate-depth Seismicity

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Intermediate-depth earthquakes that occur between ~60 and 300 km depths in subducted oceanic slabs often form a double band of seismicity. The upper band of seismicity (UBS) is predominantly within the basaltic crust and is thought to be facilitated by processes related to dehydration reactions. More controversial is the faulting mechanism of the lower band of seismicity (LBS), located within the subducted mantle lithosphere which consists primarily of olivine and orthopyroxene (Opx). High-pressure petrological studies have shown that as the oceanic lithosphere subducts to below 60-70 km depth, the Opx component undergoes an exothermic metamorphic reaction, characterized by continuous garnet exsolution to depths of ~300 km. Here, we simulate the mechanical behavior of syn-deformational metamorphosing Opx in oceanic lithosphere using controlled deformation experiments combined with acoustic emission detection and in-situ x-ray diffraction. We show that deforming Opx under the pressure and temperature conditions corresponding to those of LBS fail consistently by macroscopic faulting, accompanied with numerous acoustic emission events which are laboratory analogs of earthquakes. Microstructural analysis shows that syn-deformational metamorphism proceeds by garnet exsolution both within Opx grains and along grain boundaries. Ultrafine-grained reaction product (grain size as small as 50 nm) facilitates strain localization and weakening, promoting slip instability. An examination of thermal structures in 9 subduction zones shows that temperature conditions in these LBSs are consistent with the kinetic onset of brittle behavior observed in the laboratory, considering the tradeoff between onset temperature and strain rate. These results suggest that metamorphosing Opx likely plays an important role in intraslab earthquake processes.

Scaling Relations Between High Pressure, High Temperature Transformational Faulting Experiments and Natural Seismicity

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Acoustic emission (AE) monitoring in laboratory rock deformation experiments has served to support seismological and geophysical observations and enhance our understanding of natural earthquake processes. However, an ongoing challenge of laboratory experiments is how to scale phenomena observed under the spatiotemporal constraints of the lab (mm; a few hrs) up to those of natural earthquakes (10s of kms; 10s of Myr). In this study, controlled deformation experiments were performed under high pressure/high temperature (HPHT) conditions (~3 GPa; 700 ^{0}C) on Mg_2GeO_4 samples (3mm length; 2mm dia.) It has been shown that Mg_2GeO_4 undergoes seismogenic fracture resulting from HPHT phase transformation from olivine to spinel structure, analogous to the olivine to ringwoodite transformation which is thought to generate deep-focus earthquakes (~350-700 km). Using a mixture of sensors whose combined response spans the entire AE frequency range (0.2-20 MHz), we collected ~1500 AEs ranging in magnitude from ~-10 to -8. By filtering the waveform coda into frequency bins and applying the spectral ratio method to the coda envelopes, we are able to remove the influence of the transmitting medium, and the amplifier and sensor response functions. Additionally, by constructing probability density functions of the power spectral density we determined where sensors of differing bandwidths and resonant frequencies operate allowing us to assemble the spectral ratio over the entire frequency range. From this, we are able to determine the corner frequencies of events and, using the source model of Madariaga (1976), estimate source radii and static stress drop. Source radii range from ~0.05 – 1.0mm, consistent with sub-grain fractures to macroscopic failure. Static stress drops, which range between ~ 0.1 to 10 MPa, show remarkable similarity with previous studies of larger scale laboratory AE and natural earthquakes spanning >20 orders of magnitude in seismic moment. This suggests a self-similar rupture process from the sub-mm to km scale which is independent of pressure, temperature, stress or strain rate.

Using High Frequency Mode-converted Phases at the Plate Interface to Characterize the Properties and Along-strike Variability of the Alaska-Aleutian Subducting Plate

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The narrow zone at the top of the subducting slab where sediment and altered oceanic crust subduct has significant control on volcanism and earthquakes. Several dense broadband arrays along the Alaska-Aleutian subduction zone allow imaging of the plate interface zone and its relationship with slip events. We focus on stations and arrays deployed across the Kenai Peninsula, spanning regions of slow slip, tremor and the 1964 M9.2 earthquake rupture zone. Many signals show strong mode-converted phases (X phase) from local in-slab earthquakes (>50 km deep). The X phases show up as large amplitude, high frequency (1-15 Hz) phases between the P and S arrivals on the radial and transverse components. Their travel-time and polarization systematics indicate they come from P-S conversions at or near the plate interface, and their large amplitudes are consistent with strong velocity contrasts there. Predicted travel times for these X phases indicate they travel through a region of faster velocity than the surrounding mantle before converting from P to S. Thus, the X phase likely samples the mantle of the subducting slab and not the upper low-velocity layer as in other X phase studies. X phases are not observed for all paths and show variable detectability at adjacent stations for the same event. X phase amplitude and detectability do not vary with earthquake location and vary only weakly with station location. Instead, the X to P amplitude ratio at the conversion points varies spatially throughout the subduction zone, indicating high heterogeneity along the subducting slab interface or subducting crust over distances of a couple of tens of kms. High X/P amplitudes occur north of Cook Inlet in the slow slip region. Here, hydrated mantle is suggested by magnetic anomalies and thick underthrust sediment is suggested by a gravity low. The highest X/P amplitudes occur on the eastern edge of the array and correlate with the largest coseismic displacement during the 1964 earthquake. While X/P amplitudes vary in a complex way with frequency, they seem to be sensitive to plate interface structure at the scale of slip heterogeneity.

Complex Structure in the Nootka Fault Zone Revealed by Double-difference Tomography and a Newly Determined Earthquake Catalog

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We employ an automatic earthquake detection algorithm to seismic waveforms recorded between the years 2000 and 2020 in southwest British Columbia. 32,121 events which possess at least three paired P- and S-wave arrival times are located, compared to 21,538 seismic events in the existing Geologic Survey of Canada catalogue. This augmented catalogue is employed for double-difference seismic tomography across Vancouver Island, with particular focus on the Nootka Fault zone (NFZ). The NFZ is a transform boundary that separates the Juan de Fuca and Explorer plates in a zone of distributed left-lateral strike-slip faulting. Tomographic results indicate that a double seismic zone exists within the NFZ that parallels Vp/Vs structure typically observed in subduction zones. Specifically, a dipping high Vp/Vs layer is underlain by reduced Vp/Vs material. Structural complexities are revealed by three Mw >6 events and their aftershocks. The 2004 Mw 6.3 and 2011 Mw 6.4 events are interpreted to reside southeast of the NFZ within the Juan de Fuca plate at depths as shallow as 20 km, and the 2014 Mw 6.6 event is interpreted to reside within the oceanic plate of the NFZ at depths >35 km. Vp/Vs structure further indicates that underthrust oceanic lithosphere of the Explorer plate extends to 20 km depth beneath Brooks Peninsula. We suggest that the NFZ represents a structurally independent block of oceanic lithosphere that exhibits a more northerly trajectory than typically depicted as well as increased plate curvature when compared to either the Juan de Fuca or Explorer plates.

Structure and Seismogenesis of Subducting Slabs

Poster Session · Friday 22 April · Conveners: Yingcai Zheng, University of Houston (yzheng12@uh.edu); Neala Creasy, Colorado School of Mines (nmcreasy@mines.edu); Heidi Houston, University of Southern California (houstonh@usc.edu); Zhigang Peng, Georgia Tech (zpeng@gatech.edu); German A. Prieto, Universidad Nacional de Colombia (gaprietogo@unal.edu.co)

A Deep Dry Slab Core Beneath the Japan Sea Revealed by Inter-source Interferometry

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The intermediate- (10-100 km) and small-scale (<10 km) slab structures below 410 km are important manifestations of various thermal and petrological processes. However, seismic imaging of these structures has been particularly challenging because the seismograms recorded on the surface can be easily complicated by shallow structures. To resolve the subtle seismic signatures from deep slabs without influence from shallow complexities, we apply a novel inter-source interferometry method that turns deep earthquakes into virtual seismometers closer to the target. Using data from Hi-net, we not only present strong evidence for an intermediate-scale metastable olivine wedge and small-scale intra-slab heterogeneity beneath the Japan Sea, but also constrain their dimensions and velocity perturbations more accurately than before. The results suggest that the initiation mechanism of deep earthquakes is due to transformational faulting of metastable olivine, while revealing petrologic processes associated with dehydration of subducting slabs. Beyond the relatively independent scales of slab structures and dynamics, our findings point toward a consistent picture of a dry slab core below 410 km beneath the Japan Sea.

A Systematic Detection of Intermediate-depth Earthquakes within the Bucaramanga Earthquake Nest

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Intermediate-depth earthquakes (70-300 km depth) are generated in a deeper portion of subduction slabs where the extremely high pressures and temperatures make frictional slip unlikely. Seismicity in the deep Earth can provide essential information on the physical processes that control fluid distribution within the mantle, yet the mechanism of intermediate-depth earthquakes is still enigmatic. Under extreme conditions with high pressure and temperature in the subduction zones, three plausible models might explain the rupture process of intermediate-depth earthquakes: (1) dehydration of minerals in the subducting slab along pre-existing faults where dehydrated fluids can easily concentrate, (2) dehydration-driven stress transfer where fluid overpressures are unlikely and (3) thermal shear instabilities that account for high-stress drops and repeating earthquakes. Both models essentially depend on the local fluid distribution likely sourced from the subducting slab that controls the kinematic properties and rupture process of the fault and seismicity. The Bucaramanga earthquake nest in Colombia, where intermediate-depth earthquakes are significantly concentrated in both time and space (with a magnitude up to 6). A high-resolution catalog of Bucaramanga seismicity will likely yield key information on the rupture process of intermediate-depth earthquakes.

Here we systematically explore the Bucaramanga seismicity with matched-filtering to construct a high-resolution earthquake catalog. We use continuous-waveform data from 2015 to 2020 recorded on more than 20 seismic stations operated by the Servicio Geológico Colombiano. Our dense, detailed catalog will provide precise intermediate-depth source information such as magnitude, clustering of events into families, and correlation coefficients, that will allow us to estimate earthquake relocations, earthquake source properties via spectral analysis and seismic tomography to understand the particular conditions of the intermediate-depth source region.

An Inclusion Model for the Origin of Slab Anisotropy and the Influence on Earthquake Moment Tensors

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Subducting slabs around the deep earthquakes are shown to be strongly anisotropic (with shear anisotropy ~25%) and of the tilted transverse isotropy (TTI) because this model can explain the observed CLVD components (i.e., the compensated linear vector dipole) in the deep earthquake moment tensors in many different subduction systems. As it subducts into the mantle, a slab undergoes extreme conditions in both shear and normal stresses as well as heating. It can also cause mineral dehydration to form fluid/melt inclusions. Lattice preferred orientation of minerals can develop anisotropy under shearing, but it is hard to achieve strong anisotropy at a level such as 25%. A reasonable model to explore is the inclusion model, where aligned inclusions can result in anisotropy. We use finite element numerical modeling to compute the effective anisotropy of the inclusion model as a function of the inclusion aspect ratio and the volumetric density of the inclusions. We found that the ratio of the S-wave velocity in inclusions and the matrix should be less than ~0.1. To produce anisotropy of 25%, we found the ratio phi/*e* ~ 1.0, where phi is the volume fraction of the inclusion and *e* is the aspect ratio of the inclusion. Therefore, 1% inclusion by volume with an aspect ratio of 0.01 can generate a large anisotropy (~0.25). Possible candidates for the inclusions are fluids and carbonate melts. To further study the influence of such an anisotropy on a shear dislocation source, we will use body waves (P, S, pP, sS, ScS, PP, SS, etc.) to invert for the full moment tensors of deep earthquakes in multiple subduction zones and investigate the relationship between CLVD and non-zero trace in the full moment tensors.

Backazimuth Dependence of Shear Wave Splitting Patterns in Japan and Instraslab Anisotropy

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It has been shown that many deep subduction earthquakes (whose focal depth > 60 km) show large non-double couple components (ndcc) in the results of moment tensor analyses. These findings are used as proof to argue that deep earthquake mechanisms are different from shallow earthquakes. Recently, it was shown that there is strong evidence of high seismic anisotropy in the vicinity of deep earthquakes (subducting slabs) which can cause the observed apparent ndcc. If this hypothesis is correct, an important consequence is that the strong anisotropy in the dipping slabs can cause the observed different shear wave splitting (SWS) patterns which critically depend on the backazimuths of earthquakes as well as the slab anisotropy. We will evaluate this hypothesis in the Japan subduction zone, using Hi-net stations (>760) for global earthquakes. The preliminary results obtained from 40 stations located in Japan and 460 teleseismic earthquakes located mainly in Java and Tonga, suggest a variation of the delay time between the fast and slow S waves from about 0 sec to ~3 sec. Both the fast S polarization and the delay time have a complex relation with respect to the source location and epicentral distance. These measurements will be further used to test if a tilted transverse isotropy slab can cause the SWS observations using 3D-anisotropic elastic finite difference modeling and a propagator matrix method. Our research tries to investigate whether an intra-slab anisotropic model could simultaneously explain both the earthquake ndcc radiation patterns and the observed SWS patterns.

Characterization of the Anisotropic Mantle Lid in the Cascadia Subduction Zone

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Subducting slabs worldwide exhibit the common feature of an elastically anisotropic horizon below the oceanic Moho, the so called anisotropic mantle lid (AML). Previous studies showed that the orientation of its fast axis of anisotropy is perpendicular to the sea-floor magnetic lineations. This suggests that the horizon represents the alignment of Olivine grains during seafloor-spreading. However, the possibly high magnitude of the anisotropy and the location of the AML just beneath the oceanic Moho suggest that bend-faulting and mantle serpentinzation at the outer rise may contribute its properties. If this is the case, AML properties may be used to quantify oceanic mantle hydration.

We present receiver function images of the AML in the Cascadia subduction zone. It appears as a seismic wave conversion between 1 to 3 seconds after the Moho conversion, suggesting that it has a thickness of a few kilometres, which is variable along the forearc. The amplitude of the conversion changes with azimuth, pointing towards the anisotropic nature of the horizon. We suggest a preliminary petrophysical model that demonstrates how a detailed analysis of AML elastic properties may be used to estimate the degree of hydration of the subducting oceanic mantle.

Exploring Strain-rate Constraints on Deep Earthquake Occurrence Within Subducting Lithosphere and the Viability of Thermal Shear Instability as a Potential Failure Mechanism

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The conditions and failure mechanisms by which deep (>70 km) earthquakes occur in subducting slabs is still under investigation. The brittle failure mechanism of shallow earthquakes is inhibited by the high pressures and temperatures in subducting lithosphere at these depths. The currently proposed failure mechanisms for deep earthquakes are dehydration embrittlement, transformational faulting and thermal shear instability (TSI). Recently it has been proposed that in addition to temperature, strain-rate variations control where deep earthquakes occur: earthquakes occur in high strain-rate regions within cold subducting lithosphere. However, this high strain-rate constraint hypothesis was not tested using location specific subduction modeling nor did it differentiate between proposed failure mechanisms. Here we present an approach for deep earthquake failure mechanism investigation in specific locations utilizing subduction modeling, TSI modeling and earthquake observations. To determine the deep slab physical conditions (strain-rate, stress, temperature, pressure), location specific 2D dynamic visco-elastic-plastic subduction models with a free surface are used. To test the strain-rate constraint hypothesis, the regions of high-strain rate in the models are compared to that location's seismicity distribution as well as stress orientations from focal mechanisms. A step further, the conditions found in the high strain-rate regions of the slabs are tested in a separate 1D TSI model with matching rheology to determine if these conditions lead to TSI. Regions within the slabs found to have conditions that lead to TSI are again compared with location specific earthquake observations. This larger workflow using location specific numerical modeling and observational earthquake data helps to investigate the viability of TSI as a deep earthquake failure mechanism under high strain-rate conditions and could be similarly set up to investigate other proposed failure mechanisms.

Focusing and Multi-pathing of the Teleseismic Wavefields by the Cascadia Slab

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Even though seismic wave amplitudes have tremendous sensitivity to the structure of the Earth, they have been sparsely used compared with travel times. Structures at scales comparable to wavelengths can produce significant focusing effects. To explore this sensitivity, we conduct a series of synthetic tests and measurements on teleseismic body waves traveling the Cascadia subduction zone, where wavelengths and slab dimensions are similar. We used the 2-D, Cartesian spectral element method software package, SPECFEM2D, to investigate the focusing and multi-pathing effects of the teleseismic wavefields by simply modeling a plane wave traveling through the Cascadia subduction zone. First, we simulated the wave propagation in a simple model with a constant high-velocity slab subducting into a homogeneous background mantle. Then, we simulated the wave propagations in more realistic velocity models from thermal models (Abers et al., 2018). The state-of-art numerical simulations showed significant amplitude variations if the seismic energy propagated updip along the slab. Depending on subduction models, the variation could be twice as large. Finally, we measured the amplitude variations of long-period teleseismic body waves recorded with the iMUSH array in the Cascadia. We observed an anomalous striping pattern in amplitude along the radial or transverse direction, depending on the back azimuth of the incident wave. This stripping pattern is probably due to the interference between waves traveling through the high-velocity slab and traveling along the outer slower edge. One consequence of these focusing and multi-pathing

effects is that teleseismic body-wave attenuation measurements, which rely upon frequency-dependent amplitude changes, could be biased by the high-velocity subducting slabs.

Seismic Tomography in the Coastal Range of Chile, Between 27° and 31°S: Latitudinal Differences in the Double Seismic Zone

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From the local seismicity recorded between 27° to 31°S by an extensive network of short-period seismic stations on the Coastal Cordillera, we developed a 3D seismic tomography model. In this work, we present the seismotectonic characterization of 2 areas at different latitudes to contribute to the discussion about erosion by subduction, basal accretion, the role of hydrated minerals in subduction and the dehydration process of these, the double seismic zone (DSZ) and intraslab seismogenesis by dehydration embrittlement and/or thermal shear instability.

Our results in both areas show anomalies below the Coastal Cordillera, that are linked to accretionary complexes, which are formed by the process of tectonic erosion by dragging crustal material between the plates. This process may be exacerbated by the subduction of seamounts that first accrete in the frontal zone of the continent, building peninsulas. After that, the seamount advances deeper in the interplate zone and increases intraplate friction (producing basal accretion), leading to a loss of material (building bays) and a collapse (normal faults) in the frontal zone of the continent. About anomalies in the mantle wedge of the upper plate, our results evidence that these are latitudinally different, being linked to the amount of volatiles released from the slab, which is subject to previous conditions such as: seismicity that mobilizes fluids, fractures in the slab that allow fluid flow, metamorphic phase change in the slab, ingress of hydrated minerals to the interplate area. On the other hand, about intraslab anomalies from our results in both areas, linked to the DSZ, these allow us to interpret that at different latitudes the conditions in the oceanic mantle are also different, where in one of the areas (at 30°S) there is an anomaly of low Vp/Vs associated with normal seismicity, which may be due to dehydration embrittlement of the serpentinite and/or the thermal shear instability of anhydrous peridotite.

Systematic Detections of Intermediate-depth Earthquakes in the Subduction Zone of Japan Before and After the M9 Tohoku-Oki Earthquake and M5+ Intermediate-depth Earthquakes

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This study extends our previous work on detecting intermediate-depth earthquakes (IDEQs) at 70-350 km depth in the subduction zone of Central and Northeastern Japan. The physical mechanisms of the double seismicity zone of IDEQs are still in debate. With well-resolved double seismic layers and slab geometry, and dense seismic instrumentation, this is an ideal region to study IDEQs. In this study, we investigate the responses of IDEQs on double seismic layers to the nearby M9 Tohoku earthquake and several M5+ IDEQs since 2004. Because standard catalogs are inherently incomplete in the lower magnitude ranges, particularly right after large earthquakes when the background noises are high, we perform a systematic searching for possible missing IDEQs with the matched filter technique. Specifically, we use 69,225 IDEQs listed in the Japan Meteorological Agency (JMA) catalog between 2004 and 2018 as templates to scan through the continuous waveforms recorded by ~800 borehole stations of high-sensitivity seismograph network (Hi-net). We start with the time window one year before and one year after the 2011 M9 Tohoku-Oki earthquake. Our more complete catalog (a 2.6-fold increase compared to the standard JMA catalog) does not show a clear seismicity rate change before the Tohoku earthquake on the double seismic zone. A previous study found a clear increase in the seismicity rate on the upper plane after the Tohoku-Oki earthquake. However, we find that the contributing depth range for this change is only at 60-70 km depth. Our next step is to expand our detections in the time windows one month before and after each one of sixteen local M>=5.5 IDEQs. The event temporal-spatial distribution, frequency-magnitude statistics and aftershock productivities revealed by our more complete IDEQ catalog will help us identify which mechanism(s) is most responsible for IDEQs in this classic subduction-zone setting.

Tectonics and Seismicity of Intraplate Regions

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: Anjana K. Shah, U.S. Geological Survey (ashah@usgs.gov); Francesca Di Luccio, Istituto Nazionale di Geofisica e Vulcanologia, ROMA1 (francesca.diluccio@ingv.it); Will Levandowski, TetraTech (bouldergeophysics@gmail.com); Mimmo Palano, Istituto Nazionale di Geofisica e Vulcanologia, OE (mimmo.palano@ingv.it); Laura Scognamiglio, Istituto Nazionale di Geofisica e Vulcanologia, ONT (laura.scognamiglio@ingv.it)

Where Does the Intraplate Tectonic Activity Originate From? Examples From the Adriatic Plate

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One of the key questions in the study of intraplate earthquakes is the source of the apparent clustering of intracontinental seismicity along discrete zones and the origin of those zones? Numerous different mechanisms have been proposed to explain it and most common include stress accumulation in areas of sudden change in physical properties or in areas with structural shift. In addition, closely connected with these is the origin and transfer of the stresses deep inside the continental interiors. When dealing with earthquakes, happening hundreds of kilometres away from the plate edges (and source of stress) it can be challenging to determine the intricate connection between stress transfer and stress accumulation at some localized zone. In this context, the small Adriatic plate wedged in much larger Eurasian provides a unique opportunity to study the origin and causes of intraplate seismicity.

In this work we will show examples of two different weak continental zones in the making. The first zone is in the middle of the Adriatic plate where the seismicity is caused due to the plate fragmentation stemming from the differential stresses acting on the plate boundaries. The second one is located at the southwestern edge of the Pannonian basin, on a former suture zone which has since experienced both extension and convergence processes and is currently experiencing low strain rates but with a relatively frequent occurrence of strong earthquakes.

From the 2009 L'aquila Earthquake to the 2016 Amatrice-Visso-Norcia Sequence: 8 Years of Seismicity in Central Italy

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Central Italy has been struck by several earthquakes of moderate to large magnitude (M≥5.9) in recent years, which have caused fatalities and large economic losses. Among the most recent are the L'Aquila earthquake of 2009, magnitude 6.3, and the Amatrice-Visso-Norcia sequence, with magnitudes of 6.0, 5.9 and 6.5 respectively. In order to get better insights about the processes taking place in the region of these two sequences, we generate a new seismic catalogue via template matching from 2009 to 2016 using: (1) 19 continuous broadband stations covering the region between the epicenter of the 2009 L'Aquila earthquake in the south and the 2016 Amatrice-Visso-Norcia sequence in the north and (2) 32.074 template waveforms from the INGV catalog, constructed for all stations with at least 12 phase picks made by the professional seismic analysts of the Istituto Nazionale di Geofisica e

Vulcanologia (INGV). Continuous data and templates were filtered between 5-18 Hz and downsampled to 60 Hz for computational efficiency in a GPU-architecture. Thus, considering a detection threshold of 10 times the daily MAD of the cross-correlation functions we obtain a new seismic catalog of ~172.000 events. We quantitatively characterize the seismicity, studying the spatio-temporal evolution of the seismicity, the cumulative number of events for different regions and depths of the fault system and the interaction of seismicity using the correlation of the daily seismicity rate of each family, defined by each template and their group of detections. Our results show how complex the process that occurs between two large earthquakes on the same fault system can be.

What Is Driving the Different Types of Seismicity Related to the Alto-Tiberina Fault in Italy? Insights From a High-resolution Seismic Catalog

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The Alto Tiberina Fault system (Northern Apennines, Italy) is dominated by a low-angle (dip < 30 deg) normal fault (LANF) with several syn- and antithetic splay faults (dip > 30 deg) located in the shallow hanging wall (HW). The surface of the LANF radiates micro-seismicity in a frequent behavior which is thought to be driven by constant creep. The HW on the other hand is occasionally affected by swarm sequences, one of which was associated to a transient deformation signal and therefore thought to result from aseismic deformation as the driving mechanism.

In this study we aim to shed further light into the driving mechanisms of the different types of seismicity. Therefore, we take advantage of a high-resolution seismic catalog with a small magnitude of completeness, obtained by template matching. As a first step we use an unsupervised clustering approach to group the vast number of events into different families. A large portion of the resulting families highlight distinct fault planes which indicates that the swarm-sequence in the HW activated a complex fault network. We further examine the seismicity of each resulting family in terms of temporal clustering, the resulting effective stress drop and the space-time evolution of the seismicity along their associated fault plane. The results help to unravel insights into the driving mechanisms (pore pressure variation and fluid circulation, aseismic slip or constant creep) which are responsible for the complexity of this swarm-like seismic sequence.

Intraplate Earthquakes Near Lisbon, Portugal and the 1755 Conundrum

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The high intensities (MMI 9-10) of the 1755 earthquake in and around Lisbon—at an epicentral distance of ~250km as per tsunami-travel-time constraints—have supported very large magnitude estimates, but the search for a suitable source has been inconclusive till now. Ever since 1949, when B. Gutenberg and C. F. Richter suggested "a magnitude between $8^{3/4}$ and 9" on the basis of "the enormous area perceptibly shaken", magnitude estimates remained at that level (M8.7 in Johnston, 1996, M8.5 in Martinez-Solares and Lopez-Arroyo, 2004, M>9 in Oliveira, 2008) despite the fact that the scrutiny of historical sources led to a substantial reduction of the estimated felt area. The robust methods for the analysis of historical macroseismic data developed in the last years of the 20^{th} Century (e.g., Bakun and Wentworth, 1997) were not applied to the vast dataset available for this iconic earthquake until recently. When this was done, the outcome was significantly lower, at M7.7+/-0.5 (Fonseca, 2020). Explaining the destruction of Lisbon became an even bigger challenge.

To address this conundrum, I use the distribution of intensity outliers among the 1206 intensity datapoints—3.6% of the dataset, deviating above 2 rms residuals, all above MMI 8—to argue that the easiest explanation for the damage distribution is a multiple rupture over spatially distributed active faults, onshore as well as offshore. I assign the extreme damage in Lisbon to the occurrence of a nearby intraplate earthquake associated with the Lower Tagus Valley Fault System (LTVFS), within a few minutes from the mainshock. I present new results derived from GNSS and PSInSAR data that document the ongoing deformation of the crust around Lisbon, showing that the intraplate activity of the region is stronger than previously assumed. Finally, I discuss the implications for the seismic and tsunami hazard of the Portuguese capital.

A Conceptual Seismological Model for the Norwegian Rifted Margin Drawn from the Perspective Hyperextension

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We present a conceptual seismological model for Fennoscadia that is consistent with modern hypotheses of extended margin evolution, including post-breakup reactivation by footwall uplift in regions adjacent to sharp crustal taper. Fennoscandia's seismicity reflects the benchmark domain boundaries of its Mesozoic rifted margin: Three distinct belts of earthquakes strike subparallel to the generalized line of breakup. The outermost seismic belt marks the Taper Break (TB), or the zone of flexural coupling/decoupling between the distal (seaward) and proximal/necking (landward) domains. A coastal belt follows the Innermost Limit of Extension, defined as the onset of 39 km-thick crystalline continental crust. An interior belt follows the landward limit of the Scandinavian uplift. Between each belt, large portions of the necking, proximal and hinterland domains are seismically quiescent.

As proposed by previous authors, a first-order spatial correlation between Scandinavia's offshore earthquake belt and voluminous, geologically rapid, Neogene sedimentary loading is evident. However, the presence of thinned, faulted crystalline basement is also a very important factor behind Scandinavia's offshore seismicity. Where the Neogene deposits are thickest the underlying crust is oceanic; released energy is lower per unit area there than where lesser Plio–Pleistocene loading impacts continental crust that was fully prepared by necking and hyperextension. These data suggest that the 'strength' of the TB and the continental margin's distal domain is significantly less than that of relatively young (ca. 54 Ma) oceanic lithosphere. Our data also imply that ridge push does not contribute significantly to Fennoscandia's seismicity. Rather, we find that thin-plate bending stresses stemming from offshore depositional loading conspire with unbuttressed Gravitational Potential Energy (GPE), onshore erosion and post-glacial isostatic rebound to generate Fennoscandia's earthquakes.

Detecting Surficial Evidence of Low-rate Deformation in the Central and Eastern United States

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Detecting surface evidence of faulting in the central and eastern United States (CEUS) is challenging due to low or negligible geodetic strain rates, humid climate and anthropogenic surface modifications. Integrating multiple datasets at different spatial scales and from the surface and subsurface facilitates the identification of possible low-rate (<1 mm/yr) surface deformation. We present two case studies from the New Madrid seismic zone (NMSZ) and Eastern Tennessee seismic zone (ETSZ). In the NMSZ, we integrated fault mapping on lidar data, landscape-scale geomorphic analysis and interpretations from seismic reflection and airborne electromagnetic surveys to identify and characterize fault systems bounding Crowley's Ridge in the Mississippi Embayment. Our results suggest the faults are Quaternary-active, have slip rates <0.1 mm/yr and may be compressional stepover faults within the overall dextral Reelfoot Rift system. In the ETSZ, clear Quaternary surface deformation has not yet been identified beyond several paleoseismic trenches in the southeastern ETSZ. Here, we integrate landscape-scale geomorphic analysis, topographic lineament mapping on lidar data and limited subsurface data (seismic reflection, cores) to evaluate potential surficial deformation. We observe that changes in landscape metrics broadly align with east-west trending lineaments and previously mapped east-west Cenozoic faults. These features are optimally oriented to slip in the current stress field, generally have left-lateral senses of motion and match kinematics derived from focal mechanisms of recent earthquakes. We suggest that east-west-oriented strike-slip or oblique-slip faulting at depth may propagate upward through the Paleozoic overburden and be manifested as subtle distributed surficial deformation on 10- to 25-km-wide fault zones. These two case studies demonstrate that a multi-pronged approach may facilitate identification of surficial deformation in intraplate regions.

Complex Fault Segmentation in the New Madrid Seismic Zone Inferred From Seismicity Clustering

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P and S wave travel times from a catalog consisting of 3846 high-quality hypocenters recorded within the New Madrid Seismic Zone were used to determine a new 3D P- and S-wave velocity structure for the upper crust. The new velocity model displays, for the first time, a distinct low velocity anomaly associated with the previously proposed Boothill lineament. Joint relocation of the hypocenters in the tomographic inversion produces a new catalog of earthquake locations that are used to investigate fault segmentation. K-means clustering is used to reduce the spatial dispersion of the hypocenters by clustering events that are within 4 standard deviations of each other determined by error ellipsoid dimensions. The resulting clustered catalog is then examined to determine spatially linear features by projecting the hypocenters on viewing planes perpendicular to the line-of-sight. Individual subclusters of seismicity associated with these linear features are then extracted from the catalog and a plane is fit to the subcluster by computing its covariance matrix. The Reelfoot fault is seen to have at least 3 major segments with dips of 41 degrees, 27-35 degrees and 37 degrees, respectively from north to south. The southern segment of the Reelfoot fault is displaced northeastwards from the northern segment at the location of the northeast striking, southwest dipping Ridgely fault. The southern portion of the Axial fault is near vertical but the northern portion near the Reelfoot fault has a noticeable dip to the southeast. Assuming that the Ridgley fault and southern segment of the Reelfoot fault are thrust faults, the offset is inconsistent with the inferred right lateral stress field and suggests that both the Ridgley and southern Reelfoot faults started as primary segments of the system. Overall, faults of the New Madrid Seismic Zone are highly segmented suggesting heterogeneous basement structures and stress state.

Using Swarms of Small Earthquakes to Look for Seismically Active Structures in Northeastern North America

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Swarms of small earthquakes and microearthquakes have been observed in several different places in the northeastern U.S. and southeastern Canada over the past several decades. The modern seismic network that has operated during this time has allowed earthquakes to magnitudes below M 1.0 in these swarms to be detected and located. A relative earthquake location method allows very precise relative event locations to be computed, which can be used to look for spatial trends in the earthquake swarms. For those swarms where portable seismographs were deployed in the epicentral area of the swarms, very precise absolute locations of the swarm events can be found. Relative and absolute location analyses of 5 such swarms show a consistent pattern of the swarm seismicity aligning along known or suspected preexisting faults. These swarms, located in New York, Connecticut, Maine and New Brunswick, may be indicating which pre-existing structures in Northeastern North America might be seismically active in the future. Whether or not these structures could host a strong earthquake in the future is not clear from the data. Even so, the analyses suggest that studies of future swarms of small earthquakes and microearthquakes may help clarify the picture of which pre-existing zones of weakness may pose the greatest seismic hazard in the region.

Preliminary Analysis of Seismic Data Recorded by a Temporary Deployment Around the Source Zone of the 1886 M 7 South Carolina Earthquake

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The August 31st 1886 M~7 earthquake centered near Summerville, South Carolina is the largest historical earthquake on the east coast of the United States. Despite its significance, the source fault of the 1886 earthquake remains unknown, largely due to a lack of unambiguous surface rupture in this event. Since late May 2021, we began deploying a USGS NEHRP-funded network of L22 3-component short-period seismometers in the Middleton Place-Summerville Seismic Zone (MPSSZ); i.e., the presumed source area of the 1886 M~7 mainshock. The objective of this ~2-year deployment is to better define fault sources associated with modern microseismicity and to shed light upon the fault that ruptured during the large 1886 earthquake. As of September 4, 2021, this network has 19 stations, complementing the 4 permanent stations in the MPSSZ operated by the University of South Carolina and the US Geological Survey (USGS). Data from the open station, WSCT, is currently being streamed in real-time to the Center for Earthquake Research and Information (CERI) and from there to the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC, network code YH). Here we present preliminary results from our initial analysis of the seismic data since May 2021. Specifically, we use 30 events (19 manually identified plus 11 listed in the USGS catalog) as templates and scan through continuous waveforms to detect additional seismic events using a template matching method. In addition, we apply a recently developed machine-learning-based polarity picker to pick the first-motion polarity of selected events (including a magnitude 3.3 earthquake on September 27th 2021) and determine their focal mechanisms. Our next step is to relocate these microseismic events recorded by our dense network and use them to better illuminate subsurface faults in this region.

Buried Basement Faults Posing Potential Seismic Risk in South Carolina: Insights From High-resolution Aeromagnetic Data

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South Carolina is the site of an M~7 earthquake in 1886 and current M<4 seismicity near the M~7 epicenter in Summerville and elsewhere. In 2019-2020, high-resolution aeromagnetic data were collected over a 212x134 km area from the SC Piedmont to the Atlantic Coast, including the cities of Charleston and Columbia. We combined these data with legacy seismic reflection data to 1) image buried faults that may pose significant seismic risk and 2) better understand the geologic context of modern seismicity and the corresponding fault systems. The aeromagnetic data show numerous lineaments interpreted as Paleozoic structures, Mesozoic dikes and Mesozoic structures, including the northern boundary of the South Georgia rift basin. Within the rift basin near Summerville is a series of 15-20-km long ESE-trending lineaments, interpreted as Mesozoic faults. These terminate along >40-km long NE-trending lineaments interpreted as Paleozoic faults. Seismic reflection data show that several of these lineaments coincide with vertical offsets in Mesozoic strata and/or Cenozoic cover, suggesting fault reactivation. Additionally, S- or SE-dipping reflectors suggest that these fault systems lie within a sub-basin. With a modern stress regime of sigma-1=NE and sigma-3=vertical, less dense sub-basin fill in this area may facilitate reverse slip. The ESE-trending lineament closest to Summerville coincides with a surface scarp previously interpreted from lidar data and may have a >15-km long continuation expressed as a weaker magnetic lineament to the southeast. This and the longer NE-striking faults are thus candidates for a larger earthquake, with the ESE-striking faults more favorably oriented in the modern stress field. The aeromagnetic data also cover the Elgin-Lugoff area, where a series of M2-3 earthquakes were observed Dec 2021-Jan 2022. These earthquakes are aligned with an ~8-km long NNW-trending series of magnetic anomaly terminations within the Late Paleozoic Modoc zone. Additional monitoring may help determine whether these data delineate a causative fault.

Seismicity of Elysium Planitia, Mars

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At first glance the single tectonic plate setting of Mars implies that most of its deformation is characterized by an intraplate seismicity. Before the InSight mission, it was proposed that Martian seismicity could be driven by contraction of the lithosphere, due to secular cooling of the planet, leading to wide-spread seismicity of thrust style. Orbital images indeed show ubiquitous wrinkle ridges and lobate scarps, which are interpreted as buried thrust faults. However, over the last 3 years, InSight observed a large number of marsquakes and have shown rather a very localized distribution of the seismicity, mainly governed by normal faulting, centered around a relatively young graben system called Cerberus Fossae.

We present a working model of seismicity in Cerberus Fossae that addresses the spatial distribution of hypocenters, as well as stress drop inferred from body wave spectra. One class of events, the stronger low frequency marquakes, are located at 20-40 km depth, near the brittle-ductile transition zone. Associated low stress drops and low corner frequencies are consistent with a heated setting, possibly due to recent or possibly ongoing volcanic activity at depth. A second class of events with higher corner frequencies can plausibly be located at the graben flanks near the surface, possibly related to long-term release of residual stress from the initial opening.

Seismic Imaging of the Ups and Downs of the North American Midcontinent

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Cratons are the longest-lived tectonic features of the Earth. Although they are usually thought to be relatively stable, evidence of subsidence and uplift is widely recognized within cratonic interiors around the globe. Multiple hypotheses have been proposed for cratonic subsidence and uplift as the result of isostatic adjustments, flexural deformation due to convergence at plate margins or mantle dynamics. Understanding the formation and evolution of these cratonic ups and downs and their relationships has significant implications for the evolution of the cratonic lithosphere in general. In the past decade, the North American midcontinent has been well-covered by seismic stations, particularly with the deployments of the EarthScope Transportable Array and several Flexible Array experiments. Here we present a 3-D shear-wave velocity model of the crust and upper mantle of the North American midcontinent, using the full-wave ambient noise tomography method. We compare the lithospheric structure beneath major tectonic features in the study area, including cratonic basins, failed rifts, domes, and arches. We will discuss: 1) the scales of these features in-depth, 2) signatures of magmatic underplating beneath the basins and rifts, 3) structural and temporal relationship between the basins and domes/arches and 4) the role of plate boundary processes v.s. mantle upwelling in the formation of these features. The result of this study has broad implications for the mechanisms that drive the long-term evolution of the cratonic lithosphere.

Seismic Observations of Complex Mantle Transition Zone Structure Beneath Eastern North America

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The eastern continental margin of North America, despite being a passive margin at present, records a fascinating tectonic history of both mountain building and rifting events. In addition, several igneous events have punctuated the region's past, including the events associated with the Great Meteor and Bermuda Hotspots. To gain a better understanding of the underlying seismic structure of this region, we employ the massive quantity of seismic data recorded by the USArray to construct images of the mantle transition zone (MTZ) beneath Eastern North America. To construct these images, we first calculate receiver functions using the iterative time domain deconvolution algorithm. We then perform an automated quality control of this dataset, using our recently developed criterion, and subsequently sum the accepted receiver functions using the common conversion point (CCP) stacking technique. We show high-resolution animations and images of cross sections through these CCP stacks and highlight particular features of the MTZ discontinuity structure. Among these features are the presence of a thinned transition zone coincident with the well documented Northern Appalachian Anomaly, as well as beneath the Central Appalachians in Virgina and West Virginia. These thinned zones are in contrast to the relatively normal to thickened MTZ west of the Appalachians, beneath the continental craton. We synthesize our observations with the structure present in selected seismic tomography models, as well as with previous geologic work in the region.

Aftershock Sequences in Central/Eastern North America Last Years—Decades at Most—Not a Few Weeks, Not Millennia: Results From 149 Modern Mainshocks mw3.65–5.84

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Existing ideas about aftershock sequence behavior in intraplate settings such as central and eastern North America (CENA) are contradictory. Aftershock rates decrease as time^-p following mainshocks—termed Omori Decay—and several studies have found no significant differences between CENA decay and a "generic California" model p=1.07±0.03, implying that CENA sequences last tens to a few hundred days as do their plate-boundary counterparts. Meanwhile, some researchers assert that intraplate sequences last centuries or millennia, so most modern CENA earthquakes are merely aftershocks of historic or unknown, prehistoric events and thus belie long-term hazard. Here, in the largest study known of intraplate aftershock sequences (n=149; Mw3.65–5.84), results fall between the two extremes. Of the 149 sequences, 70 (Mw3.65–5.84; mean Mw4.2) are lively enough to be analyzed individually, 20 have no aftershocks, and the remainder are grouped geographically into 11 meta-sequences. Individual sequences average p=0.85±0.02: Omori Decay is significantly slower in CENA than California. Nevertheless, post-mainshock seismicity returns to empirical background rates over years (log-normal distribution $10^{3.0\pm0.7(1\sigma)}$; 200 days–13 years), not weeks/months as in California yet not centuries or millennia. Duration increases weakly with mainshock magnitude, such that aftershocks of a M8.0 CENA event might endure 44 years: still not centuries or millennia. Background rates, normalized by area and duration, are subtracted from normalized post-mainshock rates to quantify where de facto aftershocks occur: Nearly all are within 20 km of the epicenter, about half the radius of California models. Because most of CENA lacks known fault sources, the declustered historical/instrumental catalog is the primary source anticipated ground motion in seismic hazard models. Implementing CENA-specific declustering parameters could therefore have an important impact on seismic hazard assessments.

Refinements to the Bayesian Approach for the Calculation of Maximum Earthquake Magnitude (Mmax) in Stable Continental Regions

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The Bayesian approach introduced by Cornell in 1994 and recently used by the CEUS-SSC study (USNRC et al., 2012) with an updated database is the most widely used approach for the estimation of maximum magnitude (M_{max}) for distributed-seismicity seismic source zones in stable continental regions (SCRs). The main advantage of this approach is that it takes advantage of both worldwide data and local data from the source-zone of interest and combines these in a rigorous manner.

The conventional M_{max} approach calculates the prior distribution of M_{max} for seismic domains with a particular geologic history by calculating the distribution of $M_{max,obs}$ (the observed maximum magnitude) for these domains and then shifting that distribution in a deterministic manner using a median value of the difference $M_{max} - M_{max,obs}$ (which depends on the number of earthquakes in the source zone). To make this approach more stable, pooling of the domains is used. This study investigated an alternative approach in which the uncertainty in $M_{max,obs}|M_{max}$ in each domain is explicitly considered in computing the prior distribution of M_{max}. Two different algorithms were implemented for these calculations. Results indicate that the resulting prior distributions of M_{max} have higher means and much lower standard deviations than were previously obtained in the CEUS-SSC study. The implication is that much of the observed scatter in $M_{max,obs}$ is due to the uncertainty in $M_{max,obs}|M_{max}$, and not to domain-to-domain variation in M_{max} or to statistical uncertainty. Because the resulting prior distributions are very narrow, the effect of Bayesian updating (which combines the information from the worldwide data set with the information about the specific source zone of interest) becomes negligible.

The two algorithms yield very similar results, and Monte Carlo simulations indicate that the two algorithms are essentially unbiased.

Tectonics and Seismicity of Intraplate Regions

Poster Session · Wednesday 20 April · Conveners: Anjana K. Shah, U.S. Geological Survey (ashah@usgs.gov); Francesca Di Luccio, Istituto Nazionale di Geofisica e Vulcanologia, ROMA1 (francesca.diluccio@ingv.it); Will Levandowski, TetraTech (bouldergeophysics@gmail.com); Mimmo Palano, Istituto Nazionale di Geofisica e Vulcanologia, OE (mimmo.palano@ingv.it); Laura Scognamiglio, Istituto Nazionale di Geofisica e Vulcanologia, ONT (laura.scognamiglio@ingv.it)

A Comparison of Three Modern Aftershocks Sequences Across Southern Idaho: Characterizing the Seismogenic Zone Surrounding the Snake River Plain

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We explore spatial and temporal aftershock patterns related to three instrumentally recorded earthquakes within Idaho. Bordering the eastern extent of the Snake River Plain, within the Intermountain Seismic Belt of Idaho, we compare aftershock sequences related to the Sulphur Peak, Challis and Stanley earthquakes. Using machine learning we are able to locate low magnitude events; therefore providing a robust temporal distribution of the aftershock sequence for each earthquake. To assist hypocenter location we test a range of velocity models and the AK-135 model to determine the best hypocenter locations and lowest misfit. We increased the number of detected events from: 1,946 to 74,000 for Stanley, 189 to 7,079 for Challis and 551 to 2,916 for Sulphur Peak. Early aftershock analysis for Stanley suggests that the extent of the Sawtooth Fault may extend farther than what is currently mapped, as results show a migration of events to the North-West extent of the current fault accompanied by a change from an east to west dip direction. The Challis sequence suggests similar preliminary results to the work of others, results that show a slight migration of event locations to the east and an increase in the average depth of events when compared to the USGS catalog. Preliminary results for Sulphur Peak show an increase in depth, with a mean depth of 6.4 km, as well as a migration of events to the north-west and south-east from the mainshock, intersecting the East-Bear lake normal-fault. Using machine learning picks and the localized velocity models we were able to determine the depth of the brittle-to-ductile transition zone and note that the seismogenic zone for Sulphur Peak is found approximately ~5km< the depth of the seismogenic zone for Stanley. Parameterizing the machine learning algorithm to work on a regional scale enhances seismic detection and aids our efforts in determining the driving mechanisms responsible for these three significant seismic events.

Active Tectonics of the Central Adriatic Region: New Insights from the Recent March 2021 Seismic Sequence (Mw5.2)

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The central Adriatic Sea is characterized by a scarce background seismicity, while large shocks have struck the northern and southern Adriatic regions in the past. On 27 March 2021 an intraplate Mw5.2 earthquake occurred midway between the Italian coast to the west and the Croatian island of Lastovo to the east. Aftershocks of the 2021 seismic sequence cluster along a WNW-ESE seismic belt in the central basin where a decoupling zone of the northern and southern portions of Adria was proposed (D'Agostino et al. 2008) to accommodate the along strike change in the plate convergence vectors between the European and Adriatic plates. Moreover, if Adria is a separate microplate or a piece of the central Mediterranean puzzle that moves independently of Eurasia and Nubia is still under debate. In this work, we analyze the 2021 seismic sequence by using a multidisciplinary dataset to provide additional constraints on the kinematics of the central Adriatic region.

Delineating the Crustal Seismic Attenuation Boundary Between the Central/Eastern and Western United States

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Seismic attenuation is lower in the stable central and eastern United States (CEUS) than western US (WUS), and the USGS National Seismic Hazard Model (NSHM) applies different ground motion prediction equations in the two regions. Nevertheless, this boundary is imprecisely constrained and chiefly based on physiography and historical/instrumental seismicity rates rather than attenuation (Q^{-1}) itself. Previous crustal (Lg) Q tomography confirms the large difference between CEUS and WUS, but tomograms are not polygons, limiting their objective use in boundary delineation. To this end, we examine Q gradiometry, single-event amplitude vs. distance transects along narrow azimuth bands, and earthquake stress drop calculations to aid the NSHM in confirming or realigning the CEUS/WUS boundary. First and second horizontal derivatives envelop the Colorado Rockies and Rio Grande Rift in WUS while placing the Colorado Plateau and Wyoming Craton in CEUS. Next, inflections in amplitude vs. distance profiles for single events implicitly pinpoint changes in Q and ~1000 inflection picks are made at each of five frequencies from 0.75–12 Hz. Contouring these picks and tracing continuous local maxima objectively defines boundary polygons that largely overlap with gradient peaks. This shared boundary resembles the current one except that it includes all of the Colorado Rockies (not just the southern half) in WUS, extends the low-attenuation Colorado Plateau ~100 km farther west, and steps ~100 km farther east in Wyoming. Inflections also delineate the Midcontinent Rift and Gulf Coast margin more clearly than other previous approaches. Finally, we calculate stress drops from CEUS, WUS and Colorado Rockies earthquakes and compare recorded ground motions with NGA-East and NGA-West2. The Colorado events display WUS affinities, confirming the more northern boundary. Sensitivity tests are underway to quantify the impacts of changing the boundary in the 2023 NSHM or future editions.

High-resolution Receiver Function Analysis of the Pecos, Texas Region

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The Delaware Basin in West Texas is a large, hydrocarbon-rich sedimentary basin that has been that has been the site of increased hydraulic fracturing for natural gas production and associated wastewater injection over the past decade. During this same time period, there has been a several orders of magnitude increase in seismicity, including earthquakes as large as 5.0M. This increase in seismicity associated with hydraulic fracturing and fluid injection has spurred a number of studies focused on understanding the mechanics and hazards associted with these earthquakes, as well as the structure of the basin more generally as the geophysical context for underlying the earthquakes. In this study we utilize data recorded from 2018 to 2020 around Pecos, TX by the University of Texas at El Paso with funding from the Texas Seismological Network (TexNet). This network (The Pecos Array) includes a backbone of ~25 5-Hz, 3-Component Magsesis Fairfield seismic nodes sampling at 1000Hz and deployed for 14 months, as well as several additional deployments for one or more months. We supplement this data with publicly available TexNet data from West Texas to calculate receiver functions, focused on the region within approximately 100km of Pecos, Texas. Our study builds on previous receiver function studies of the greater Permian Basin region using USArray and TexNet data by adding additional resolution in the Pecos, TX region. By utilizing our nodal seismometer array, we are able to observe smaller scale structural features that are possible with broader regional data.

Joint Inversion of HVSR and Surface Wave Group Velocity Dispersion to Characterize Shallow Sediments at the Monahans Dune Field, West Texas

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The Monahans Sandhills are one of many large eolian systems in the Southern Great Plains region. Investigations into the Monahans dune systems have identified paleosols and pluvial lake sediments interbedded within the eolian sands, suggesting a highly variable monsoonal history. Sonic borings, advanced dating techniques and small-scale geophysical surveys have identified primarily Holocene to Pleistocene eolian and paleosol deposits infilling a common, pre-Pleistocene, clay paleo-surface, thus marking a distinct unconformity in the stratigraphic record. From interpolations of the aforementioned surveys, the paleo-surface is shown to exhibit remarkable variability in thickness. As more extensive boring is cost prohibitive, we use passive-source seismic methods to characterize the dunes and to delineate the eolian/clay contact.

We acquired ambient noise seismic data for two weeks with a set of three rolling deployments of 150 SmartSolo IGU-16HR 3C (5Hz) seismic sensors. Each deployment aimed at a different target within the Monahans dune system: a shallow limestone lacustrine deposit, the paleo-surface that underlies the entire study area and the western edge of the active dune structure. We use horizontal-to-vertical spectral ratios (HVSRs) and surface wave group velocity dispersion in a joint inversion that uses a global optimization technique to characterize each target. Broad searches of the model space allow us to characterize the uncertainty, nonuniqueness and ambiguity in model parameter estimates in both individual and joint inversions. From these experiments, we conclude that, although modeling with HVSR or surface wave dispersion alone is highly nonunique, their complementary sensitivities impose stronger constraints on model parameters in a joint inversion. Nonuniqueness of parameter estimates is reduced markedly in the joint inversion with respect to inversion of either HVSR or surface wave dispersion alone.

Mapping the m5.8 Mineral Earthquake Aftershock Sequence and the Virginia Seismic Zone

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Little is known about actively deforming structures, seismicity and seismic hazard in the Central and Eastern United States (CEUS), because of low strain rates, sparse seismicity and consequent sparse monitoring networks especially in comparison to the western USA. Newly developed data mining techniques that detect orders of magnitude more small earthquakes have the potential to provide a higher resolution and detail of seismicity in these regions. In this project, we aim to draw a detailed picture of the seismicity, and related seismic hazards in Virginia, by detecting earthquakes too small to have been observed previously. A high-resolution mapping of earthquakes is essential to inform future estimates of seismic hazard to identify active structures,especially in the CEUS where there is little correlation between mapped structures and seismicity. Building upon published catalogs created during temporary experiments, we present a preliminary catalog of the whole Central Virginia Seismic Zone and zero in on the aftershock sequence of a major CEUS earthquake, the M5.8 Mineral Earthquake of 2011.

The 2021 Milford, UT Earthquake Swarm

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An earthquake swarm occurred in Spring 2021 in south-central Utah near the town of Milford. The University of Utah Seismograph Stations located 125 earthquakes between March 19 and May 10 with magnitudes ranging from 0.53 to 3.23. We implement a matched-filter technique in order to identify additional earthquakes that went undetected during the routine network location. The 125 network-located earthquakes are used as templates and are cross-correlated with continuous data for the dates Feb 17 – June 10. This time period corresponds to approximately one month before the earthquake swarm began through one month after it ended. For the matched-filter analysis, we rely heavily on station FOR1, which is located within 5 km of most template events. Four other stations within 20-30 km of most template events provide a supplement to the closest station. The matched-filter implementation resulted in the detection of over 1000 earthquakes in addition to the original 125 catalog events. Routine locations suggest a west-dipping fault, and we further investigate structures revealed in the seismicity by relocating both templates and detections using the double difference method. Hydrothermal features in the area, including a geothermal power plant, suggest that fluids may be a contributing factor to the earthquake swarm triggering. Thus, we examine the role of fluids by determining diffusion and migration characteristics of the swarm seismicity.

The Seismicity of West Africa: Construction of a Focal Mechanism Catalog with a Sparse Dataset

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The dynamism of Earth is expressed through earthquakes, reflecting the rheology and stress condition in the lithosphere, the plate-tectonic forces affecting the arrangement of continents and seismic hazards that ultimately determine the fate of humans. While much is known about the origin and driving mechanism of earthquakes both globally and in other regions on the continent, in the case of West Africa, despite the growing trend of earthquakes, the causes of the seismicity have been left understudied. This is due to limitations including, but not limited to, sparse seismic networks, and a very insufficient focal mechanisms catalog. We address some of these short-comings in this study. We focus on improving the resolution of the stress field and the kinematics of the region based on an updated focal mechanism catalog for earthquakes with magnitudes between 3.5 and 5.0.

We develop techniques to characterize the source mechanisms in the sparsely instrumented regions of West Africa using a combination of classical and modern methods of Moment Tensor Inversion. The approach is similar to that used for studying source mechanisms on Mars which only has a single seismometer. We combine first P-motion, linear inversion, and grid search of both multiple stations and single station earthquake-body waves to determine the focal mechanism solutions of 247 earthquakes in West Africa. Preliminary results are showing much promise. Our study of particularly interesting earthquakes in Algeria, Niger, Guinea and Mauritania reveal the components of the regional stress regime and suggest anthropogenic influences on fault reactivations in Mauritania, at the edge of the West Africa Craton. We expect that our study will shed light on this poorly studied region of the world and will allow us to understand how and why earthquakes happen in stable intraplate regions of our planet.

Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources

Oral Session · Wednesday 20 April · 8:00 AM Pacific

Conveners: William R. Walter, Lawrence Livermore National Laboratory (walter5@llnl.gov); Catherine M. Snelson, Los Alamos National Laboratory (snelsonc@lanl.gov); Robert E. Abbott, Sandia National Laboratories (reabbot@sandia.gov)

Oceanic Microseisms in Alaska

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The objective of this work is to analyze the spatial variation of microseisms across Alaska and their variations through time. We also identify the primary source locations of these microseisms. Quantifying and locating microseism is important because it provides complementary ways to view multi-decadal evolution of sea ice extent, wave heights and storms in north pacific and might help in improved tomography and nuclear monitoring. We select 154 stations across Alaska and western Canada and base our analyses on hourly power spectral densities of the seismic data. We create time histories of the various microseism bands by applying a median filter of seven hours and interpolating gaps of less than 12 hours. These adjustments minimize the influence of earthquakes and highlight temporal patterns that are daily to monthly in scale. We compare these power time series to environmental parameters including collocated barometric pressure, ocean wave heights and sea ice extent.

A rich history of literature has demonstrated different ocean wave sources for the primary and secondary microseisms, which are generally observed in the period ranges of 10-30 seconds and 5-10 seconds, respectively. We find that waves in the Gulf of Alaska tend to create higher amplitude microseisms than waves of equivalent height in the Bering Sea. This may be due in part to the wide continental shelf extending into the Bering Sea. To infer the actual source of microseisms we use the spatial patterns observed across Alaska. We find that the spatial gradient of the microseism power typically points toward regions of ocean with the highest significant wave height. This gradient direction moves in sync with the west-to-east trajectory of major storm systems. This method successfully tracks storms in the Gulf of Alaska. It also tracks storms in the Bering and Chukchi Seas. Storms in the North Atlantic are rarely the dominant source of microseisms in this region. However, the influence of North Atlantic storms is at times quite clear especially in northern and eastern Alaska.

Analysis of Sustained and Extensive Tidally Triggered Seismicity on the Ross Ice Shelf

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The Ross Ice Shelf (RIS) is the largest ice shelf on Earth. It lies in a complex environment where stresses related to changes in temperature, ocean swell, tidal phase and other perturbations generate many periodic ice quake swarms. We detect and categorize these events using a cross correlation template library assembled from detected transient signals. The highest quality events are located using polarization analysis to determine source direction and Rayleigh phase dispersion to estimate distance source-receiver distance. Local magnitudes are computed to approximate source size. We use this data to characterize some of the mechanisms which underly at least two classes of tidally driven cryoseismic events. The most common of these appears to result from the formation of near surface crevasses which develop from stresses induced edge flexure. A second class of events is correlated with tidal high stand. We utilize the specfem2d synthetic seismogram package and a noise cross correlation-derived firn model for the RIS to create synthetic seismograms to test hypotheses related to possible intra- and sub-ice source mechanisms. Understanding the mechanisms of these cryoseismic events will our understanding of brittle processes affecting the RIS and its response to changes in environmental conditions.

Insights From Trapped Seismic Waves in Antarctic Firn Columns: Flow Related Anisotropy, Temporal Monitoring and Rayleigh Wave Behaviors

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Surface waves in Antarctic firn display unusual behaviors when excited by local high frequency sources. Multiple data sets recorded across varied instrument types and array configurations present pervasive narrow band spectral features above 5 Hz with temporal variability responding strongly to atmospheric forcing events such as storms, deposition/stripping and thermal forcing. These spectral peaks furthermore display splitting along horizontal axes that match azimuthal anisotropy measurements directly estimated through active source experiments, and frequency dependence of splitting maps to various scales and depths of independently correlated structural features. Further studies of anthropogenically excited surface waves at an array near WAIS Divide show basin-like effects in high-frequency Rayleigh waves including spatially variable particle motion reversals and multi-mode H/V amplifications correlated with firn trapped waves, suggesting that the latter observations are likely driven by Rayleigh waves as well. The exotic nature of firn wavefields is further highlighted by the broad range of physical observations that can be obtained at individual isolated stations.

This wealth of information obtained in the firn seismic wavefield highlights the usefulness of broad, sparse deployments of seismic sensors for site measurements of multi-scale temporal and structural parameters.

Identifying Stable Body-wave Sources for Correlation-based Seismic Velocity Monitoring

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Human activities leave strong imprints on seismic recordings; however, these seismic signals have conventionally been treated as unwanted noise. Recent studies have demonstrated the feasibility of combining seismic interferometry and anthropogenic seismic signals to probe Earth structures and monitor seismic velocity changes in active tectonic regions. Retrieving high-frequency (> 5 Hz) seismic body waves travelling through the upper crust is of great interest, as they provide high spatial resolution and are less susceptible to shallow environmental perturbations. However, identifying sufficiently energetic sustainable body-wave sources is not trivial. We propose a workflow, based on the stability of cross-correlation functions to pinpoint regions with dominant body-wave sources. Specifically, we tackle the problem from a statistical point of view, considering that sustainable, energetic seismic sources yield highly coherent correlation functions among close by stations, and therefore converge faster. We design a random selection process to quantify the correlation convergence rate and use it as a criterion to find regions of potential interest. We test the procedure in California and Japan. Multiple regions, including the Anza area (San Jacinto Fault), Ridgecrest, and the central part of Japan show great potentials. Array analysis at Anza (Piñon Flat observatory) enables us to further identify strong sources in that region, which are mainly freight trains in the Coachella valley.

Characterizing Emergent and Impulsive Non-tectonic Signals in Seismic Waveforms

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The proper classification of emergent and impulsive seismic noise is critical for detection of microearthquakes and developing a complete understanding of ongoing weak ground motions. Tectonic events occupy a small percentage of each day and seismic records contain numerous natural and anthropogenic signals. Recent studies have demonstrated that ongoing low-amplitude ground motion is dominated by various weak sources originating at the surface from anthropogenic and atmospheric interaction. Characterizing new classes of waveforms originating from wind generated ground motions, air-traffic, automobiles and other non-tectonic signals can provide insightful information when designing a machine learning training data set. In 2014 a dense array (0.36 km^2) of 1,100 vertical geophones recorded ground motions on the San Jacinto fault for 30 days. The data provides detailed waveforms to detect microearthquakes and observe surface and atmospheric processes that manifest as impulsive and emergent signals. Unsupervised machine learning is applied to label 5 classes of non-stationary seismic noise common in continuous waveforms. Temporal and spectral features describing the data are clustered to identify separable types of emergent and impulsive waveforms. The trained clustering model is used to classify every 1 second of continuous seismic records from a dense seismic array with 10-30 m station spacing. The results show dominate noise signals can be highly localized and vary on length scales of 100's meters. The methodology demonstrates the complexity of weak ground motions and improves the standard of analyzing seismic waveforms with a low signal-to-noise ratio. Application of this technique will improve the ability to detect genuine microseismic events in noisy environments where seismic sensors record earthquake-like signals originating from non-tectonic sources.

A Semi-empirical Method for Producing Broadband Synthetic Seismograms for Large, Rapid Landslide Scenarios

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There is an increasing push to develop seismoacoustic early warning systems for cascading hazards caused by large landslides such as long runout lahars or tsunamis. These systems are contingent on detecting and characterizing a causative landslide as early as possible. However, the events of interest are rare, making calibration and validation difficult, and there is currently no methodology for generating synthetic data for landslide scenarios to test such systems. In this study, we present a semi-empirical method for simulating synthetic signals for landslide scenarios that uses seismic recordings of past landslides, and thus the method does not require a numerical landslide model or complex seismic wave propagation modeling. We use records of past small landslides that occurred at the site of interest for modeling high frequencies (>1 Hz) and large landslides that occurred elsewhere for intermediate (0.2-1 Hz) and low frequencies (<0.2 Hz). We also demonstrate another approach that allows for modeling of specific scenarios using numerical landslide models (e.g., D-Claw). The low frequencies in both approaches are modeled deterministically using simple 1D earth models and are matched with stochastically simulated intermediate and high frequency energy. The spectral scaling patterns of the stochastic portion of the signal are derived from seismic records of large, rapid landslides in the IRIS Exotic Seismic Event Catalog. The scaling of the highest frequencies, which are most affected by local site factors that are difficult to model, is based on real recordings of smaller landslides at the site of interest when available. We demonstrate the approach in two regions where early warning systems are under development: the Barry Arm landslide that could fail catastrophically, threatening the town of Whittier, Alaska, with a tsunami and Mount Rainier, Washington, where large landslides and resulting lahars could reach populated areas.

Seismo-acoustic Characteristics of the Cooling Tower of a Research Nuclear Reactor

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Seismic and acoustic characteristics of a cooling tower at the High Flux Isotope Reactor, a research nuclear reactor at Oak Ridge National Laboratory, were investigated using data from three targeted experiments that were carried out during 2019–2021. We used spectrograms, power spectral density, an interactive frequency picking tool and ground truth information to study seismic and acoustic responses due to the operation of pumps and fans located near or on top of the cooling tower. By varying the operating speed of the fans, we found that a faster fan speed leads to higher seismic and acoustic energy. A stepwise increase in fan speed leads to a station-specific stepwise pattern in seismic spectrograms. At each fan speed and for each fan, different impulsive frequencies can be identified using the interactive frequency picker. Seismic responses of two fans operating concurrently are equivalent to the summation of seismic responses of each fan. We can match the acoustic response of fans from one targeted experiment with that from three actual operational cycles of the High Flux Isotope Reactor. Seismic responses of the fans show significant differences at different stations even for the same fan operating at the same speed, though common impulsive frequencies can be found in most cases. Unlike the fans, seismic responses of the cooling tower pumps contain mostly broadband features in the frequency band of 5–50 Hz (or 5–150 Hz for some stations). Clear seismic responses of the three cooling tower pumps were observed at all seismic stations up to a maximum distance of 120 m. As expected, seismic energy is higher when the sensor is located closer to the source. We were able to locate the source of pump-related seismic responses using absolute amplitudes of seismic signals. The inferred source location region includes the actual location of the pump, which can be improved with a polarization analysis of seismic signals.

Kinematic Source Inversion of Acoustic-seismic Signals of a Meteoroid Explosion Recorded on a Large-N Seismic Network and Fibre Optic Cables

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A meteoroid exploded in the upper atmosphere on July 2, 2021 close to the city of Reykjavik, Iceland and was widely reported. We use an outstanding record of local, dense large-N seismic sensors and distributed acoustic sensing observations (DAS) to study the trajectory and kinematic properties of the bolide. The dense seismic network was installed at the Hengill geothermal field as part of the DEEPEN project and includes high-quality observations from seven seismic arrays with a few hundred meters aperture, a total of 500 3-C geophones, DAS strain-rate measurements along two fibre optical cables and an infrasound array. All sensors are located within the distance range of 300 km.

The high-frequency recordings display multiple trains of acoustic wave arrivals from the disintegrating meteoroid that are coupled to the surface of the Earth and recorded by the instruments. The complex signal shows two strong phases and multiple weak arrivals, which can be identified coherently in the DAS data and within the nodal data. A delayed phase up to 25 seconds later can be resolved on parts of the DAS cable and few of the nodal stations

We present a finite-length kinematic line-source pulse model that consistently explains the different phases inside and outside the Mach cone segment of our images, their wave amplitude variations, and a polarity change between the first and terminating phase. The previously undiscovered rich directivity effects of a bolide explosion can also explain the seemingly contradictory time-dependent wave energy beam-directions at the small aperture arrays and along the DAS cable. A Bayesian inversion of first and stopping phase arrivals led to a precise localization and geometry of the trajectory and the kinematic properties of the moving meteorite.

The DEEPEN project is a collaboration between the Eidgenössische Technische Hochschule Zürich (ETHZ), German Research Centre for Geosciences (GFZ), Iceland Geo-survey (ISOR), and NORSAR.

On the Seismic Equivalence of Chemical and Nuclear Explosions: Insights for the Source Physics Experiment

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Chemical and nuclear explosives differ in the way they contain and release energy and how that energy is converted to ground motion. These differences are important to understand so chemical explosions in field experiments, such as the Source Physics Experiment (SPE), can be used as surrogates in monitoring research for banned nuclear explosions.

Initially, it was assumed that chemical explosions produced equivalent ground motion to nuclear explosions given the same yield (i.e., seismic equivalency factor of one) because the relationship between yield and ground motion derived from nuclear explosions worked well for small chemical explosions (Denny & Johnson, 1991). However, numerical prediction and experimental observation of the large kiloton chemical source used in the Non-Proliferation Experiment (NPE) found a factor close to two increase in ground motion relative to predictions from historical nuclear relationships (i.e., seismic equivalency factor of two).

The inconsistency is resolved when we consider that a nuclear explosion source may have a varying energy density while a chemical explosion source has a more constant, and relatively much lower, energy density. Those differences result in a high energy density source, like a nuclear explosion, losing more energy to plastic work, which could represent energy losses due to vaporization, melting and damage, than a chemical explosion.

In doing so, we review the theory by Haskell (1961) and Glenn (1993) and extend it to the application of chemical to nuclear seismic equivalencies with comparison to numerical simulations. Theory and calculation show that at low yields the equivalency is near unity and as the yield increases to around one kiloton the equivalency increases to near two, consistent with NPE observations. Further, the results show that the equivalency factor can increase to values greater than two for yields more than one kiloton.

We will discuss the implications of these results for interpreting observations from SPE, as well as explosive yield inference in general.

Discriminating Explosions From Earthquakes and Collapses With Seismic and Acoustic Waves

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For the past 40 years, all declared nuclear tests have been underground, leading to seismoacoustic waves being the most robust way to find them. To monitor for such explosions, particularly at low yield, their signals must be discriminated from a background of other sources including earthquakes and cavity collapses. To improve capabilities, a series of chemical explosions were conducted at the Nevada National Security Site in southern Nevada to supplement legacy nuclear test data. These include: 1) the NNSA DNN R&D sponsored Source Physics Experiments (SPE) and 2) the DTRA sponsored Large Surface Explosion Coupling Experiment (LSECE). The three-part SPE has completed two Phases to date: Phase I in saturated granite from 2011-2016 and Phase II in dry alluvium from 2017-2019. Data from these well-instrumented experiments is improving our understanding of the physics that underlies methods to distinguish between source types using seismoacoustic waves. For example, Pyle and Walter (2021) demonstrate the explosion P/S ratios show remarkably little systematic variability with depth, scaled depth, yield and emplacement media changes. In contrast, overall amplitudes and thus yield estimation are very sensitive to these effects. This is consistent with explosive S-waves coming from P-wave generated scattering and conversion effects and has implications for P/S discriminants applications. Other discriminants such as moment tensors and ML-Mc are more dependent upon emplacement and depth effects. We are exploring machine learning methods with and without including known discriminants to improve our understanding of seismoacoustic source differences. The degree of dependence of seismoacoustic amplitudes on emplacement and depth has implications for the transportability of discriminants. Finally, we are starting the third Phase of SPE to directly compare earthquake and explosion sources with common media and depth to really put our physics-based models to the test.

Things That Go Bump: Identifying and Characterizing Non-Earthquake Seismo-Acoustic Sources

Poster Session · Wednesday 20 April · Conveners: William R. Walter, Lawrence Livermore National Laboratory (walter5@llnl.gov); Catherine M. Snelson, Los Alamos National Laboratory (snelsonc@lanl.gov); Robert E. Abbott, Sandia National Laboratories (reabbot@sandia.gov)

A Major Update to the Exotic Seismic Events Catalog: A Compilation of Seismogenic Mass Movements

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We present an update to the collection of seismogenic mass movements that forms the basis of the Exotic Seismic Events Catalog (ESEC), doubling the number of events in the catalog from 121 to 242 while broadening the geographic distribution and range of event types. The ESEC is available online through IRIS's searchable product depository or as a downloadable SQLite database from USGS ScienceBase. This update adds more instances of seismogenic landslides, debris flows, snow avalanches, outburst floods and lahars as well as some new event types: two mine collapses, a submarine landslide and a volcanic flank collapse. We also now incorporate infrasound detection. Whereas the first version of the catalog focused on mass movements located primarily in the Western United States and Canada, this update includes events from Europe and Pacific Islands. We only include events for which seismic data are openly available.

We provide both basic seismic information (e.g., station detections on different frequency bands, seismic data location, etc.) and ancillary data such as geometric measurements, references, photographs and satellite imagery. When available we use published values such as source location, drop height, runout distance and volume, and when not documented, we estimate values from satellite imagery or photographs. Events are categorized in terms of the quality of the ancillary data, and we provide estimates of uncertainty on parameters such as location and volume. This update increases the availability of seismogenic mass movement data to the community to promote research that betters our understanding of event dynamics and improves methods for exotic event detection, classification, and characterization. Future updates could allow for the incorporation of other exotic event types like blasts and glacial events. The ESEC has a mechanism for community members to contribute events to the collection, so we encourage other researchers to join in the effort.

Arrival Time Based Seismoacoustic Source Location Using a Bayesian Framework

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Accurately locating seismoacoustic events is a continuing topic of interest within the monitoring community. The high variability in atmospheric temperatures and winds makes modeling infrasound source-to-receiver traveltimes highly uncertain in comparison to infrasound array direction of arrival estimates and seismic arrival times. As such, previous seismoacoustic location methods combine infrasound backazimuth estimates from arrays of infrasound stations with seismic arrival times to determine spatiotemporal location estimates, along with a confidence region representing the uncertainty in that location. Although array-based location methods represent the standard for infrasound source location, global infrasound arrays are limited due to design requirements (multiple sensors, large aperture (typically >1 km)) and high deployment and maintenance costs. Conversely, single infrasound stations require minimal effort to deploy, but lack the ability to provide direction of arrival estimates. In this study, we expand on an existing seismoacoustic location method to include arrival times from single sensor infrasound stations. We utilize the celerity-range priors from the improved Bayesian Infrasound Source Localization (BISL) method to account for variability in the atmosphere as well as across a network. First, we demonstrate the viability of this method by using arrivals on single-station infrasound sensors in the absence of array-based arrival times and backazimuth estimates. Next, we include seismic observations in a joint location to reduce the uncertainty. This study demonstrates the feasibility of spatiotemporal location using a variety of observation and instrument types which increases location capabilities in areas of sparse instrumentation. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Detecting Landslides in the Barry Arm Region Using Long-period Signals

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Coastal landslides present a hazard that is thought to be increasing as the climate warms and fjords that were once glaciated become ice-free. Unstable fjord walls create an obvious landslide hazard with the potential in some cases to initiate catastrophic local tsunamis. In this study, we use the unstable mountainside of the Barry Arm as the focal point to study a hazard that spans much of coastal Alaska.

We examine the viability of using near-source seismic data to detect and locate landslides in real-time, using the Barry Arm seismic network as the type example. The two broadband sensors situated within ~ 5 km from the slide have recorded a handful of smaller landslides since deployment in summer 2020. Our initial analyses suggest that these events generate coherent long-period seismic signals (< 0.1 Hz), which can be observed rapidly at near-distance stations. We exploit the waveform similarity observed in these stations and develop a routine to detect and locate potential landslides based on long-period signals. Here we present results from different detection and location methods applied to these recent landslides. We also test these approaches on continuous data in the Barry Arm region and on historical landslides. These provide a unique contribution to coastal landslide monitoring systems on a real-time basis.

Refining First-arrival Traveltime Picks of Active Seismic Data for Improving Structure Characterization at Rock Valley, Nevada

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A seismic survey was conducted at Rock Valley, Nevada, to prepare for Phase III of the Source Physics Experiment (SPE) and to improve the existing 3D velocity model of the area. The multi-component seismic dataset was acquired using an accelerated weight drop (AWD) source at 25-m intervals along two intersecting roads, creating 553 source locations, and 188 three-component receivers placed along six receiver lines with a 100-m receiver interval. The AWD source was configured to create P- and S-waves using one vertical and two 45° hits orthogonal to the source lines. The recorded signals at far offsets are weak but crucial for tomographic reconstruction of the velocity model at km depth. We address the challenge of picking weak first-arrivals to improve structure characterization.

We improve the accuracy of first-arrival traveltime picks using the following procedure. Rather than picking on common-shot gathers (CSGs), we enhance trace visual coherency using bandpass filtered common-receiver gathers (CRGs). The CRGs of the Rock Valley seismic data have a trace spacing of 25 m, which is smaller than the 100-m trace spacing of the CSGs. To enhance visibility of far-offset traces, we apply automatic gain control (AGC) to each CRG. We further enhance visibility of the first arrivals by superimposing wiggle traces onto gray-scale plots. We use initial manual picks to select windowed signals containing the first arrivals to perform deconvolution and obtain zero-phase traces. We then pick the first-arrival peaks of these traces to reduce pick uncertainty. Using this procedure, we can pick first-arrivals at offsets over 3000 m. Our accurate first-arrival traveltime picks from the near- to far-offset traces can improve traveltime tomography for subsurface velocity model building.

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Regional Moment Tensor Inversion of the Western United States Using a Three-dimensional Earth Model

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The use of regional distance long-period, complete waveform data to determine the seismic moment tensor is a routine and reliable approach in determining the source mechanism of natural and manmade seismicity and is used to identify or discriminate different types of seismic sources. However, seismic source characterization is dependent upon having a well-calibrated Earth model to compute the synthetic Green's functions for the inverse problem. Although one-dimensional (1D) Earth models are good approximations for real Earth structure to model regional-distance, long period surface waves, to extend the moment tensor inversion method to lower magnitude events and to greater distances requires higher fidelity Earth models to capture the three-dimensional (3D) variations in subsurface material properties. Recent advancements in computational capabilities have greatly improved the performance of 3D-wavefield simulations, thus greatly reducing the computational resources needed to calculate 3D synthetic Green's functions for full waveform source inversion. Using a 3D radially anisotropic Earth model from adjoint waveform tomography we quantify the improvements in seismic source characterizations relative to using a 1D Earth model for an existing waveform data set of explosions, collapses and earthquakes from the western United States. We compared the results at different period bands: 20 to 50 seconds and the impact of lowering the minimum period to 10 seconds. The use of a 3D model improves the overall goodness-of-fit between data and synthetics and reduces the amount of time shift required to align the waveforms and synthetics. Moment tensor source-type analysis also showed a better constrained moment tensor source when we accounted for 3D wave propagation effects. The details of the 3D Earth model can be found in the accompanying presentation by Rodgers et al., 2022.

Spatio-temporal Variation of Ambient Noise in the Sikkim Himalaya

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Ambient noise characteristics are studied at the newly constructed 27 seismic stations in Sikkim Himalaya, installed to study the seismogenesis and subsurface structure. Power spectral densities obtained for the ambient noise recorded in the vertical component of the seismometer lies within the defined global noise limits. The horizontal components tend to record noise higher than the global noise limits due to its higher susceptibility to induced tilts. Comparison of the installation methods reveals that the instruments installed above the ground records higher long-period noise than those installed below the ground. Changes in the geography and population density across the region induces spatial and temporal variations in short-period and microseism noise. Day-time records higher cultural noise than night-time, while microseism noise dominates during monsoon. A study of the effect of the nationwide lockdown imposed due to the COVID-19 pandemic revealed a significant drop in the short-period noise recorded at stations located in regions with higher anthropogenic activity. Our study summarizes the overall ambient noise patterns, validating the stability and performance of the seismic stations across the Sikkim Himalayas.

Variability and Precision of Acoustic-to-seismic Coupling from Explosions Recoded Across Albuquerque Seismological Laboratory

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Acoustic energy originating from explosions, sonic booms and thunderclaps have been recorded on seismometers many times since the 1950s. The seismic response has generally been interpreted to arise through excitation of Rayleigh waves through a variety of mechanisms. However, at lower frequencies (< 0.05 Hz) seismic excitation in response to wind-driven variations in atmospheric pressure have been inferred to arise though a direct, nonpropagating (i.e., generating ground motions that do not propagate elastically in the Earth and are incoherent over spatial scales of less than a wavelength) deformation of the emplacement material surrounding the seismometer. Seismic responses to both high-frequency (> 40 Hz) and low-frequency (< 0 .02 Hz) pressure variations have recently been used to infer near-surface material properties including velocity structure and elastic moduli. In this study, we use a small aperture (about 600 m) array of broadband seismometers to understand the fundamental nature and repeatability of seismic excitation from 1 to 15 Hz using horizontally propagating acoustic waves generated by local (2 – 10 km) explosions. We find that sensors emplaced in granite do not record ground motions consistent with retrograde elliptical motion predicted by acoustic-to-seismic coupling theory. We conclude that the observed seismic signals arise predominantly through nonpropagating strain of the granite in response to changing pressure with almost non-existent influence from sensor tilt. We find that within one wavelength, consistency of recorded ground motion amplitudes decays linearly with station spacing distance. Therefore, we recommend that if acoustic-to-seismic coupling is used to constrain near-surface properties, the seismometer and infrasound sensor should be co-located to minimize uncertainty in the material property estimates.

Variations in Ambient Seismic Noise of the California Central Coast

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We seek to quantify patterns in ambient seismic noise related to environmental forcings of the California Central Coast. Nonlinear interactions between ocean waves and shoaling with the seafloor cause the primary and secondary microseisms between approximately 0.05 and 1 Hz, while higher frequency noise (>1 Hz) is typically associated to cultural and environmental sources. We use three years of broadband seismic data to explore systematics of seismic noise in the 0.01-2 Hz frequency range to constrain the seasonal and long-term noise characteristics in our study region. Data for this study comes from an ongoing seismic micro-array deployment in Sedgwick Reserve in the Santa Ynez Mountains. Power spectral density and probability density function estimates for seven seismic stations show largely consistent primary and secondary microseismic peaks, as well as seasonal patterns in spectral amplitude and waveform shape. Our data have also shown the potential influence of tidal signals on spectral amplitude. We will test for linkages between these patterns and environmental factors by comparing the spectra with meteorological data for precipitation, windspeed, and ocean wave height. Differences across stations despite their proximity provide insight into the influence of shallow sediment heterogeneities and surface geology on the resulting ambient spectra.

Using Data and Experience to Improve Geohazards Communication

Oral Session · Wednesday 20 April · 2:00 PM Pacific

Conveners: Wendy Bohon, Incorporated Research Institutions for Seismology (wendy.bohon@iris.edu); Scott Johnson, UNAVCO (scott.johnson@unavco.org); Lisa Wald, U.S. Geological Survey (lisa@usgs.gov)

Earthquake Science Communication in Stable Continental Regions

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Stable Continental Regions typically have relatively low levels of seismicity, so the level of public awareness of earthquakes is often low or non-existent. Earthquakes are perceived as things that happen in other parts of the world, so when the ground does shake it has a greater impact on the population due to the unfamiliarity of the experience.

At 9:15 a.m. on Wednesday, 22 September 2021 (2021-09-21 2315 UTC), a majority of the population in southeastern Australia felt the Mw5.9 Woods Point earthquake, and in many cases it was their first earthquake. It was felt strongly (MMI IV) by millions of people across Melbourne, 130km to west of the epicentre, and to lesser intensities in other cities up to 1000km away including Sydney, Canberra, Hobart and Adelaide. When an earthquake like this occurs, public interest is high and presents a rare opportunity to educate a mass audience about earthquakes in Australia, explain how the region differs from other parts of the world, and remind people what to do during strong shaking.

Social media platforms allow information to be spread rapidly throughout the wider population, with scientists less reliant on news media cycles and platforms for science communication. The most popular platforms of Facebook, Twitter, Instagram and TikTok will reach a majority of the public in the shortest time, but radio and TV news are still important as trusted sources.

What is the key to effective science communication? How do we ensure the information is relevant and accessible to a diverse audience? Explaining scientific concepts such as ground motion attenuation, intraplate earthquakes and aftershock forecasts needs to be done using analogies that are appropriate for the target audience. People are reassured when they understand what is happening, so good science communication is important for managing public anxiety during major events.

Effective science communication requires practice to be able to confidently perform while under pressure of an unfolding event. The concepts communicated evolve from questions from the public and media, but the messages must remain simple and consistent.

Impact of the National Seismological Service (Mexico) Outreach Activities

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Mexico is a very seismic active country, with an average of an M 7.0 or above every other year. Therefore, the need for dissemination in seismology that contributes to society's knowledge of the seismic phenomenon is obvious. Said knowledge and its appropriation is at the base of the integral management of seismic risk. For this reason, the National Seismological Service (SSN) of the Institute of Geophysics of the National Autonomous University of Mexico, institution in charge of monitoring seismicity in the country, has adopted the vision to be a reference in seismology outreach. In this work, we analyze how the population has perceived the impact of the dissemination activities by the SSN and if they have contributed to the appropriation of knowledge about seismology. We also analyze the trust that people has in the SSN as an institution with a scientific base whose main objective is the dissemination of information about the earthquakes that strike Mexico. In particular, we analyze the program "Platicando con un sismólogo" ("Chatting with a seismologist"). This program initiated in June 2017 and consists of a monthly Facebook Live. A seismologist is invited to answer all the questions posted by the viewers. We analyze its impact and the evolution of the questions and the participation of the viewers.

A Decade of Creating Data Visualizations for Online Video Content: The Pacific Tsunami Warning Center's Earthquake and Tsunami Animations

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As part of its outreach efforts toward mitigating tsunami hazards, the Pacific Tsunami Warning Center (PTWC) began posting computer animations to its first official social media site, it's Facebook Page, in August of 2012. Nearly a year later, in June of 2013, PTWC also gained a YouTube channel and has been posting new content there ever since. PTWC produced its initial video content for these sites by adapting the data visualizations it had previously generated for a NOAA Science-on-a-Sphere (SOS) exhibit at Honolulu's Bishop Museum. PTWC had originally adapted these SOS visualizations from the map displays it developed for its tsunami warning operations showing historic earthquake and tsunami activity and of tsunami forecast model output. Through 2015 PTWC experimented with display style while releasing new animations on the anniversaries of significant historic tsunamis and for Tsunami Awareness Month in Hawai'i. At the same time PTWC continued to develop its animation code, ultimately leading to real-time wave-propagation animations for both YouTube and SOS. Through collaboration with an outreach specialist and with feedback from colleagues and test audiences PTWC then created a standardized set of animations of historic tsunamis and global earthquake activity for both YouTube and SOS, and again released individual animations to the public on significant anniversaries over 2016-2017. From 2018 through 2020 events prompted the creation of animations focused on seismic activity at local and regional scales for Kīlauea Volcano, Puerto Rico, and California. Since then PTWC has continued to innovate with new animations for recent and historic events such as three simultaneous tsunamis in 2021 and a 120-year sequence of historic earthquakes and tsunamis. Links: https://www.youtube.com/user/PacificTWC; https://sos.noaa.gov/.

Communicating ShakeAlert® with an Online, Educational Animation: Project Overview and Preliminary Evaluation Results

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In 2021, the ShakeAlert® Earthquake Early Warning (EEW) system expanded from California into Oregon and Washington, making public alerting available in all three West Coast states. Operated by the US Geological Survey, ShakeAlert detects seismic waves, rapidly estimates the earthquake's magnitude, intensity and location, and shares that information with delivery partners who send alerts to mobile devices and automated systems, giving people critical seconds to prepare for shaking. ShakeAlert has the potential to protect lives, property and infrastructure in the earthquake-prone US West Coast. With this new technology, however, comes the need to increase public awareness and understanding of ShakeAlert, so that people have appropriate expectations of the system and know how to respond if they get an alert.

As part of a multi-pronged effort to address this need, the ShakeAlert Educational Resources Working Group developed a 4-minute animation, available online in English and Spanish. Using lay language and graphics, the video explains how ShakeAlert works, including a discussion of P and S waves, the "late alert zone," and Drop, Cover and Hold On.

Evaluation of the video was conducted to assess 1) how, and to what degree, the video contributes to learning outcomes—specifically changes in knowledge, awareness, interest and/or intended behavior related to ShakeAlert; 2) how those outcomes differ across demographic groups; and 3) what factors contribute to or hinder the video's accessibility and/or understandability. To address these areas of inquiry, qualitative and quantitative data were collected via online surveys and virtual interviews from English- and Spanish-speaking individuals in Oregon, Washington and California. In this session, we present preliminary data derived from this study and discuss what those data mean for the animation in question, as well as for geoscience communication and education more broadly.

Assessment of the General Public's Understanding of Rapidly Produced Earthquake Information Products Shakemap and Pager

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Public engagement through outreach is a key mechanism for learning about science and to communicate societal impacts. However, outreach effectiveness could be limited if approaches are not evidenced-based. Partnerships with cognitive scientists who study fundamental learning processes suggests helping people learn how earthquakes happen would improve understanding of hazards and motivate preparedness. We used a seismology-cognitive science partnership to evaluate understanding by non-geoscientists of widely-viewed USGS ShakeMap and PAGER products originally developed for technical use. After discussions with USGS staff, we constructed 13 free response questions probing understanding of these products and included the Graph Literacy Scale (GLS) for comparison. Through Zoom interviews of 100 participants, we found poor performance (28% correct) on the PAGER and ShakeMap questions despite good performance (76% correct) on the GLS. When coding free responses, we identified an average of 12.4 misconceptions per participant, ~1 per question. 5 misconceptions were observed in over half the participants, including how reports are constructed and used in real time, that reports are estimations not observations, and difficulty interpreting probabilities. The performance and misconceptions led us to develop a revised PAGER with scatter plots to visualize fatality and damage probabilities among other simplifications. We used a multiple-choice survey to assess understanding using the original and new visualizations with another 100 participants. We found significant improvement: 49% correct when seeing the revised visualization first, compared to 36% when seeing the original visualization first. Finally, we surveyed ~150 participants whether they could distinguish expert-defined shaking/damage descriptors for three macroseismic terms (moderate, strong, and severe). Participants struggled, choosing greater consequences than intended. Our findings suggest key aspects of earthquake products are poorly understood by non-geoscientists, but adjustments can improve their effectiveness when disseminating information to the public.

Using Data and Experience to Improve Geohazards Communication

Poster Session · Wednesday 20 April · Conveners: Wendy Bohon, Incorporated Research Institutions for Seismology (wendy.bohon@iris.edu); Scott Johnson, UNAVCO (scott.johnson@unavco.org); Lisa Wald, U.S. Geological Survey (lisa@usgs.gov)

GeoGateway for Higher Level Analysis and Visualization of Data

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GeoGateway (https://geo-gateway.org) is a powerful analytic center framework that enables users to integrate disparate data sources for intuitive and rapid science analysis. It provides tools to understand earthquake fault systems through the use of UAVSAR and GNSS data integrated with earthquake fault, seismicity and model data. GeoGateway has expanded to include applications of observations of the 2017 Thomas Fire in California and subsequent Montecito debris flows. Disaster-related applications can be of use to emergency responders, and should therefore be shared more widely beyond the scientific community. Scientific articles are often used to communicate results, but expanding the types of media used to communicate findings is vital to communicating science to the public at large, from novice to expert geoscientists. Effective communication about geohazards to a heterogeneous audience is beneficial to allow for disaster preparedness and the ability to make informed decisions regarding public safety. NASA's airborne and satellite-based instruments provide Earth science data that aid in understanding natural disasters, tectonic processes and environmental change. NASA data are free and openly accessible but can be challenging to use, which is why a comprehensive understanding of how to use these datasets is of paramount importance. To invite a wide range of users from different backgrounds to effectively use GeoGateway to further analyze and better interpret geohazards, we developed a User Guide, tutorial videos, introductory exercises, social media outlets to communicate results and a new user interface to allow for intuitive, rapid visualization of data in a simplified workflow.

What Controls the Style of Fault Slip in Subduction Zones?

Oral Session · Wednesday 20 April · 2:00 PM Pacific
Conveners: Qingyu Wang, Massachusetts Institute of Technology (qingyuwa@mit.edu); Alice-Agnes Gabriel, Ludwig Maximilian University of Munich (alice.gabriel@web.de); Keisuke Yoshida, Tohoku University (keisuke.yoshida.d7@tohoku.ac.jp); William B. Frank, Massachusetts Institute of Technology (wfrank@mit.edu)

Insights Into the Occurrence and Characteristics of Near-trench of Slow Slip Events at the Hikurangi Subduction Zone From Some Recent Seafloor Geodetic Experiments and IODP Observatories

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Resolving the distribution of transient slow slip event (SSE) processes at offshore subduction zones is hampered by the difficulty of measuring offshore crustal deformation. Two methods are overcoming these challenges: (1) using ocean bottom pressure sensors to discern seafloor pressure changes due to vertical deformation and (2) measuring pore pressure changes in subseafloor observatories as a proxy for formation volumetric strain. Both approaches have been employed (concurrently with deployment of ocean bottom seismometers) at various locations along the Hikurangi subduction zone offshore New Zealand, with the goal of capturing near-trench SSEs and their relationship to seismicity. We present preliminary results from a seafloor pressure sensor/OBS deployment undertaken in 2020/2021 to capture vertical deformation during a May 2021 SSE offshore Pōrangahau at the central Hikurangi subduction zone. The Pōrangahau SSE occupies the along-strike transition from deep interseismic coupling to aseismic creep.

We will also present new insights into offshore Hikurangi SSEs from two IODP borehole observatories installed in 2018 at northern Hikurangi, located within a few kilometres of the source of large, well-documented shallow SSEs. Formation pressure data reveal pressure changes equivalent to 0.1 to 0.3 microstrain during a large 2019 SSE. The subseafloor observatory data (together with onshore GNSS and seafloor pressure data) constrain the distribution and evolution of slip during the 2019 SSE and require a maximum of 20 cm of slip at 6-7 km depth, with up to 10 cm of slip <10 km from the trench. The locus of early peak slip corresponds with peaks in expected dehydration of subducting volcaniclastic material, indicating possible influence from fluid overpressure. Our models further demonstrate that incorporating realistic near-surface elastic moduli (constrained by in-situ LWD measurements) is required to fit borehole strain and surface displacement data simultaneously.

Can Stochastic Modeling Capture Slip Distributions for M9 Events?

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While stochastic slip rupture modeling is a reduced-physics approximation, its power lies in its capabilities to create thousands of unique large magnitude ruptures based on few statistical assumptions with computational efficiency. Earthquake early warning systems, hazard assessments and infrastructure response can benefit greatly from this technique. Yet a fundamental question pertaining to this approach is whether the slip distributions calculated in this way are realistic. More specifically, can stochastic modeling reproduce slip distributions that match what is seen in M9 events recorded in instrumental time? We first start with the 2011 M9.1 Tohoku-Oki earthquake and tsunami where we test both a stochastic method with a homogeneous background mean and a method where slip is informed by an additional interseismic coupling constraint. We test two constraints with varying assumptions of either trench coupling or creeping and assess their influence on the calculated ruptures. We quantify the dissimilarity of slip distribution between the modeled ruptures and a slip inversion for the event. In addition to the slip pattern, we model tsunami inundation with high resolution for over 300 ruptures and compare the results to an inundation survey along the eastern coastline of Japan. We conclude that stochastic slip modeling can produce ruptures that can be considered “Tohoku-like”, gathered from both slip distribution and the resulting tsunami hazard. Applying a coupling constraint to the ruptures produces considerable variation on its ability to model “Tohoku-like” ruptures, which may in turn lead to misrepresenting hazards in future studies. Next, we show that for other great earthquakes such as the 1960 M9.4-9.6 Chile and 2004 M9.1-9.3 Sumatra stochastic slip modeling has the capability to produce realistic ruptures. Finally we will discuss briefly how these findings can be used in the context of early warning systems where synthetic ruptures can be used to train advanced machine learning algorithms.

What Makes Low-frequency Earthquakes Low Frequency: Cluster-based Constraints on the Attenuation Structure of the Nankai Plate Interface, Japan

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The Nankai Trough (Japan) hosts many slow earthquakes that could potentially precede, and even, trigger a large subduction zone earthquake. Constraints on the physical mechanisms responsible for slow earthquakes are essential to understand this potential interaction. Tiny repetitive earthquakes with a characteristic low-frequency signature, called low-frequency earthquakes, often accompany slow earthquakes and can act as a probe to interrogate the physical conditions of the plate interface.

We select two 10 km-radius depth columns of the Nankai Trough, one where LFEs regularly occur and one where they do not, to develop a cluster-based approach to estimate both the source properties of earthquakes below, above and at the subducting plate interface. We first apply the empirical Green's function (eGf) approach using closely located small earthquakes as eGfs for larger, collocated earthquakes. We are then able to retrieve the local site effects and the empirical attenuation functions (eaf) to obtain displacement spectra of the earthquake source. Initial inversion of the local attenuation structure suggests a low attenuation zone at or near the plate interface, where low-frequency earthquakes occur. With constraints of this low-attenuation layer, we can more accurately estimate the properties of the low-frequency earthquake source and quantify the relative contributions of path and source to their characteristic low-frequency signature.

CASIE21 Seismic Reflection Images Reveal Potentially Active Splay Faulting at Dynamic Backstop in Cascadia Accretionary Wedge

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Splay fault rupture during megathrust earthquakes increases vertical seafloor displacement and consequently, tsunami size. Earthquake rupture modeling shows splay fault rupture is promoted by stress barriers in the accretionary wedge. Recent large megathrust earthquakes (e.g., 1964 Alaska Mw 9.2, 1944 Tonankai Mw 8.2, 2004 Sumatra Mw 9.2) exhibited splay fault rupture at rock strength/lithologic boundaries in the accretionary wedge, called backstops. This suggests backstops are effective stress barriers that may promote splay fault rupture. The CAscadia Seismic Imaging Experiment 2021 (CASIE21) on the *R/V Marcus G. Langseth* collected ultra-long-offset multi-channel seismic (MCS) reflection data over the Cascadia subduction zone outer forearc. In this study, we use preliminary shipboard MCS images from the CASIE21 cruise to examine the dynamic backstop offshore Washington and northern Oregon, which is the boundary between the younger, weaker Plio-Pleistocene wedge and the older, stronger Olympic-Franciscan wedge. Previous studies using legacy MCS data and seafloor morphology hypothesized that splay faults are active near the dynamic backstop in this region. Using preliminary imaging based on early shipboard processing, we find the dynamic backstop corresponds with changes in faulting style (landward to seaward vergence), seafloor elevation and slope (flat to steep) and seismic character (coherent to incoherent). We also observe possible fault plane reflectors near the dynamic backstop. These observations further suggest potentially active splay faulting at the dynamic backstop that could rupture during the next Cascadia megathrust earthquake. However, further processing of the MCS data is needed to confidently interpret fault extent and geometry at depth and to clarify relationships between the splay fault and the megathrust fault. We anticipate that this analysis will be useful in incorporating potential backstop-controlled megathrust splay fault rupture into hazard assessments for future earthquakes and tsunamis at the Cascadia subduction zone.

Unsteady, Uniform Rupture Growth Revealed by Tectonic Tremors in Cascadia

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Slow slip events (SSEs) in the Cascadia subduction zone are marked by tectonic tremors that track the migrating slip front. We cluster a catalog of 180,000 tremor epicenters into 1056 swarms and analyze the rupture of their underlying SSEs. Using new methods to measure both swarm area and duration, we find that all SSEs converge to a uniform growth pattern described by a single power-law, $A(t) \sim Kt^n$, with exponents that vary between 0.5 and 1.0 for larger, reliably fit events. This uniform SSE growth, however, is only apparent when we redact intermittent pauses in tremor activity. We suggest that these pauses reflect unsteady propagation of the slip front and excluding them removes rupture complexity to reveal a diffusive-like slip process and underlying universality in growth. These observations imply the propagation velocity, v_{prop}, may also be described by a power law ranging between ~ $t^{-3/4}$ and $t^{-1/2}$. Slip propagation starts relatively fast and slows as the rupture progresses by up to an order of magnitude for the largest events, which terminate at speeds of ~20-40 km/day. Notably, this process does not reset after a temporal pause, which implies an effective 'memory' or path-dependent evolution in the fault response to loading as the rupture grows. Our observations suggest all ruptures start and grow nearly identically, and their eventual size is not predetermined, but controlled by external factors.

Empirical Low-frequency Earthquakes Synthesized From Tectonic Tremor Records

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Tectonic tremor and low-frequency earthquakes (LFEs) are two different representations of the high-frequency (>1 Hz) components of broadband slow earthquakes, which have been discovered in various tectonic regions. Although LFEs are considered building blocks of tremor, it is difficult to find constituent LFEs for some long-duration tremor sequences. Here we introduce a new scheme to synthesize an impulsive response from a tremor source, or empirical LFE (eLFE), from complex tremor sequences. The eLFE is constructed by maximizing the absolute amplitude (L_∞ norm) of the normalized and stacked waveforms of many tremor sequences at many stations. This problem includes a highly multimodal objective function, which is maximized via a combined optimization method that incorporates a genetic algorithm and iterative improvements. We first apply this method to several validation tests using synthetic tremor waveforms and real LFEs and then tremor activities where few nearby LFEs have been detected. One example is the Okayama tremor, which has been known to be extraordinarily sensitive to tidal stress. The eLFE is helpful in determining the accurate hypocentral location and recovering the long-term comprehensive tremor activity via a matched-filter analysis. The well-constrained depth of the Okayama tremor sources is less than 30 km, which suggests that the subducting Philippine Sea Plate is very shallow at this distant location from the trench axis. This eLFE scheme highlights the fact that tremor sequences may be composed of random fluctuations that are not necessarily impulsive and emphasizes the importance of characterizing such randomness to better understand slow earthquake behavior.

Widespread Very Low Frequency Earthquakes (VLFEs) Offshore Cascadia

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Seismogenic zone is typically considered as a frictionally homogeneous zone producing regular fast earthquakes, including large damaging ones. So far, Cascadia subduction zone has largely conforms to this idea. Episodic tremor and slip (ETS) has been observed in the deeper transition zone onshore, but very little sign of slow earthquakes has been observed offshore near the seismogenic zone.

Here, we discover very low frequency earthquakes (VLFEs) offshore Cascadia with widespread distribution covering northern and central Cascadia subduction zone. Using data from ocean bottom seismometers, we found 12 distinct VLFE families with hundreds of repeats and almost daily activity over the 5 months time period analyzed. We apply a centroid moment tensor inversion and match filter method, which are successfully used to detect and locate deep VLFEs in Cascadia (Ghosh et al., 2015; Hutchison and Ghosh, 2019). Offshore VLFEs are distributed along dip all the way between the trench and coastline. Interestingly, a VLFE cluster lies spatially close to a cluster of offshore regular earthquakes, indicating that seismogenic zone in Cascadia maybe frictionally more heterogeneous that previously thought. The discovery of offshore VLFEs in Cascadia suggests that the slow earthquake does occur offshore near seismogenic zone, potentially influencing state of stress in fault segment that is capable of nucleating megathrust earthquakes. Detail investigation of offshore VLFE activities provides new insights into the physics of slow earthquakes, its interaction with regular fast events, tsunamigenesis, moment release, slip and fault behavior in an area capable of producing M9 earthquake.

Analysis of Eight-year-long Low-frequency Earthquake Catalog for Southern Cascadia

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Low-frequency earthquakes (LFEs) are small magnitude earthquakes, with typical magnitude less than 2, and reduced amplitudes at frequencies greater than 10 Hz relative to ordinary small earthquakes. Their occurrence is often associated with tectonic tremor and slow slip events along the plate boundary in subduction zones and occasionally transform fault zones. They are usually grouped into families of events, with all the earthquakes of a given family originating from the same small patch on the plate interface and recurring more or less episodically in a bursty manner. In this study, we extend the LFE catalog obtained by Plourde et al. (2015, GRL) during an episode of high tremor activity in April 2008, to the 8-year period 2004-2011. All of the tremor in the Boyarko et al., (2015, EPSL) catalog south of 42 degrees North has associated LFE activity, but we have identified several other, mostly smaller, clusters of LFEs and extend their catalog forward and backward by a total of about 3 years. As in northern Cascadia, the down-dip LFE families have recurrence intervals several times smaller than the up-dip families. For the April, 2008 Episodic Tremor and Slip event, the best recorded LFE families exhibit a strong tidal Coulomb stress sensitivity starting 1.5 days after the rupture front passes by each LFE family. The southernmost LFE family, which has been interpreted to be on the subduction plate boundary, near the up-dip limit of tremor, has a very short recurrence time. Also, these LFEs tend to occur during times when predicted tidal Coulomb stress is discouraging slip on the plate boundary. Both observations suggest this LFE family may be on a different fault. Further analysis of this LFE family will be presented.

Emergence of Repeating Earthquakes Along the Mexican Subduction

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The Mexican subduction zone is characterized by a silent earthquake zone (a.k.a. The Guerrero Gap) surrounded by areas of elevated seismicity. This dichotomy has become more evident in recent years by the occurrences of four large Mw7+ class earthquakes that rupture near the boundaries of the Guerrero Gap and by the rupture of two nearby asperities in the Ometepec-Pinotepa Nacional region. Several studies point out that both, the irregular geometry of the plate interface and the fluid release in the region, play important roles in the changes of seismicity rates along the trench, as well as the interaction between slow slip events and large thrust earthquakes. Here, we present the results of the spatio-temporal analysis of repeating earthquakes near the ruptures of recent four Mw7+ earthquakes: (1) 2012 Mw7.5 Ometepec earthquake, (2) the 2014 Mw7.3 Papanoa earthquake, (3) the 2018 Mw7.2 Pinotepa Nacional earthquake and (4) 2021 Mw7.1 Acapulco earthquake. We examine under what conditions these Mw7+ events were preceded by an increase in the activity of the repeating earthquakes and what are their corresponding source mechanisms (stress drop, rupture area). As more repeating earthquake families are discovered, repeating earthquakes may provide a valuable tool to estimate temporal changes in the seismic hazard along the trench and to pinpoint the nucleation zones of future ruptures.

Time-domain Source Parameter Estimation of Mw3-7 Earthquakes in Japan

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The omega-squared (ω^2) source model and the corner frequency (f_c) of the displacement spectrum are widely used to estimate earthquake source parameters. The source spatial scale (a) is usually indirectly estimated from f_c with the assumption that f_c is inversely proportional to a. However, if the rupture pattern is complex, the f_c vs. a relationship is non-unique. To overcome this difficulty, we apply a time-domain deconvolution method to high-quality seismic network data in Japan and systematically address the source complexity and the radiated energy (E_R) for 1,736 Mw3-7 earthquakes.

We first determine the apparent moment-rate functions (AMRFs) of the earthquakes using the empirical Green's functions. Some AMRFs have multiple peaks, suggesting complex ruptures at multiple patches. We then use the AMRFs to estimate E_R of the events having more than ten reliable AMRFs. We find no strong dependence of the scaled energy (e_R=E_R/M_0) on the seismic moment (M_0), focal mechanisms, or depth. The scaled energy varies by about one order of magnitude between earthquakes, with a median of about 3.5×10^{-5}, which is comparable to the values obtained by previous studies.

We then measure the source complexity by the radiated energy enhancement factor (REEF; Ye et al., 2016) defined by the ratio of E_R to the minimum scaled energy for the given M_0 and source duration. REEF does not show strong scale dependence for Mw3-7 earthquakes. REEF varies approximately from 1 to 50, reflecting the diversity of rupture complexity. About a third of the events have REEF>5 and show multiple pulses on the time domain. The spectra of such complex events deviate significantly from the ω^2 model, and f_c is poorly defined. Thus, applying a simple ω^2 model with f_c to complex ruptures can result in significant source parameter estimation errors.

What Controls the Style of Fault Slip in Subduction Zones?

Poster Session · Wednesday 20 April · Conveners: Qingyu Wang, Massachusetts Institute of Technology (qingyuwa@mit.edu); Alice-Agnes Gabriel, Ludwig Maximilian University of Munich (alice.gabriel@web.de); Keisuke Yoshida, Tohoku University (keisuke.yoshida.d7@tohoku.ac.jp); William B. Frank, Massachusetts Institute of Technology (wfrank@mit.edu)

Nature of the Volcanic Upper Crust of the Hikurangi Plateau: Implications for Megathrust Structure and Hydrogeology

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Hydrological and mechanical processes within subduction zones that ultimately control the nature of shallow (>15 km depth) megathrust slip are often attributed to the properties of subducting sediments and topographic irregularities of the oceanic basement (e.g., seamounts). Compared to trench sediments, the contribution of fluids within upper oceanic crust is typically minor (~1.5-5 wt. %) and not subject to substantial compaction induced dewatering at shallow depths. New results from the NZ3D and SHIRE seismic surveys at the northern Hikurangi margin, a subduction zone renowned for shallow slow slip events, do not follow this notion. Here, the subducting oceanic plate is part of the Hikurangi Plateau, a Cretaceous-age large igneous province with thickened crust and numerous volcanic edifices. P-wave velocities estimated with 3D full-waveform inversion reveal seismic velocities consistent with the top of mature oceanic crust (4.5 km/s) are ~3 km below the top of low-velocity (2-4.5 km/s) Cretaceous volcanics. Although no clear basement reflection defining the top of oceanic crust is observed, layered seismic reflections are prevalent within the 3-km thick low-velocity volcanic unit. Many of these layered reflections are adjacent to volcanic cones and upon 3D inspection are interpreted as stacked volcanic intrusions with circumferences on the order of 5-10 km. P-wave velocities within the low-velocity volcanic unit are laterally heterogeneous, possibly as a result of magmatic intrusions within sediments or lateral variations between extrusive volcanics and volcaniclastics. Future work will establish bounds on water content with effective medium theories that account for mineral-bound and pore-bound water. These observations suggest that at the northern Hikurangi margin thick, fluid-rich volcanics have the potential to deliver substantial water to the megathrust and that mechanically weak layers within the volcanics may support deformation including compaction and shear.

Slow Slip Dynamics Reproduced by Symptomatic Low-frequency Earthquake Activity

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Geodetic positioning is the geophysical record of reference to study slow slip events, but it only reveals the large-scale dynamics of slow slip. We realize a multi-disciplinary analysis of a 3-year period which contains a 6-month long Mw7.5 2006 slow slip event (SSE) in Guerrero (Mexico) using both GNSS positioning and low-frequency earthquake (LFE) activity at daily and sub-daily time scales. We estimate seismic fault slip from LFEs using three independent seismological observables and the aseismic slip at the interface from surface displacement recorded by GPS stations. We define a simple model of fault slip on the plate boundary that represents the competition between long-term loading due to the plate convergence and intermittent slow slip release, as estimated from the fault-slip time history of LFEs. We show that our LFE model only fits the geodetic estimates of fault slip with long-term loading rates on the order of plate convergence, implying 100% coupling on the plate interface at short time scales. We also highlight that the seismically estimated fault slip of LFE activity is roughly consistent with the aseismic slip generated by transient slow slip events. As the studied period includes a Mw7.5 SSE, seven smaller Mw6.4 events, and Mw<5.5 daily slow transients, all of which are interspersed with intermittent periods of tectonic loading, a power-law scaling between seismic and aseismic fault slip is necessary for our model to fit the data. To quantitatively assess the power-law exponent, we invert our model during different time periods. For the entire 3-year period, a scaling exponent of 2 is necessary, while for the large 2006 SSE, a linear relationship is preferred. We explain the difference in scaling exponent implies that the LFE source region becomes saturated when the area of slow slip extends updip; the power-law exponent must be increased to weigh the large slow slip events more compared to smaller transients. Based on our results, we suggest that LFEs are a seismic symptom, but not an intrinsic feature, of slow slip and are a powerful in situ monitor of aseismic fault slip until they're not.

Tectonic Tremor Localization Using Bayesian Inversion

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Periodically-occurring slow earthquakes in northern Cascadia produce low-frequency seismic signals including low-frequency earthquakes (LFEs) and tectonic tremor. Methods to locate the sources of these two types of events often yield results that do not coincide but both are thought to originate near the subduction interface. As such, whether LFEs and tremor result from the same processes and where those processes are located remain open questions. In this study, we produce a catalogue of tremor sources from an episodic tremor and slip (ETS) event beneath Vancouver Island, Canada, using a new location method. Our method includes processes that automatically detect tremor signals, construct datasets using waveform-envelope cross-correlation, remove outliers, estimate data error statistics and use a grid-based Bayesian inversion to locate source positions and quantify uncertainties from the resulting 3D probability distributions.

We first test this method on local crustal earthquakes and obtain well-constrained relocations within an average of 3.5 km in epicenter and 4.5 km in depth of official catalog values. We then locate tremor during the November 2019 ETS event and find that source epicenters are highly clustered with rapid migration between clustered patches. Consistent with other studies, we show source depths peak at ~30 km depth, which is 10 km shallower than current slab surface models and LFE locations. The relatively shallow and distributed depths of well-constrained tremor sources suggest either that ETS slip occurs within a shallow vertically-distributed shear zone or that a significant portion of tremor is produced in the lower continental crust. Additionally, the shallower occurrence of tremor relative to LFEs suggests different source processes. Application of our location technique to additional ETS events will help to better understand the locations of tremor sources and thereby infer potential physical processes of ETS tremor generation.

Triggering Dynamics of Tremor-like Events During Laboratory Hydrofracturing

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The modes of fracturing in Earth materials exhibit a wide spectrum of time and length scales. Some fractures propagate slowly, such as slow earthquakes and earthquake swarms, while others propagate fast, such as typical earthquakes. The upper bound of the rupture velocity is controlled by material properties, but the lower bound is not well known. Slow and fast motions may coexist. For example, episodic tremor and slip (ETS) are semi-periodic phenomena characterized by the simultaneous occurrence of slow earthquakes and tectonic tremor. In this study, we explore the relation between seismic and aseismic processes that occur during a laboratory experiment. We hydro-fracture a PMMA (rigidity~1GPa) transparent sample and simultaneously image the rupture using a high-speed camera and listen to the "pops" using piezoelectric sensors under ambient pressure and temperature conditions. During the hydro-fracturing experiments, the fluid stresses a circular tensile crack that propagates as driven by strength of the materials. The large crack propagates at a speed of 60 m/s, or 8% of the Rayleigh wavespeed. At the same time, we triangulate the arrival times of acoustic emissions (AE) signals to locate where sudden short-lived ruptures occur at the rupture front. We find that the cumulated radiated energy emitted from these AE events is proportional to the area of the overall crack. This observation matches the recent observation of the radiated energy of tremor being proportional to the size of the slow slip earthquake. Such a similar scaling law measured by both laboratory and field experiments may provide a better comprehension in the mechanics of subduction megathrusts.

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