SSA 2014 Annual Meeting Announcement

Seismological Society of America
Technical Sessions
30 April–2 May, 2014
Anchorage, Alaska

IMPORTANT DATES	
Meeting Pre-registration Deadline	23 March 2014
Hotel Reservation Cut-Off	07 April 2014
Online Registration Cut-Off	18 April 2014

PROGRAM COMMITTEE

This year's technical program committee is composed of:
Jeff Freymueller - co-chair (University of Alaska, Fairbanks)
Peter Haeussler - co-chair (USGS, Anchorage)
David Wald - board liaison (USGS Denver)
Geoff Abers (Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY)
Lloyd Cluff (Geosciences Director Emeritus Pacific Gas & Electric, San Francisco, CA)
Christine Goulet (University of California Berkeley, Los Angeles, CA)
Rich Koehler (State of Alaska, Div of Geological and Geophysical Surveys, Fairbanks, AK)
Thorne Lay (University of California, Santa Cruz, CA)
Stephanie Prejean (USGS Alaska Volcano Observatory, Anchorage, AK)
Julian Lozos (UC Berkeley, Berkeley, CA)

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TECHNICAL PROGRAM

The following special sessions have been formed for the technical program. Additional sessions may be added based on submitted abstracts.

75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding

Since the power-law scaling of the earthquake-size distribution has been documented for the first time by Ishimoto and Iida in 1939, 75 years ago, it has become most commonly characterized by the b-value in logN=a-bM, published in 1944 by Gutenberg and Richter and cited more than 1500 times since then. A multitude of studies have since been devoted to uncover the nature of b: From suggestions of being universal and unity to reports of significant spatial and temporal variation. From global catalogs to local microseismicity and acoustic emissions in laboratory experiments. From natural earthquakes to induced seismicity. From statistical robustness analysis to b-value imaging and physical interpretation.

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Beyond these aspects, the b-value is frequently used in seismic hazard analysis for linking the observed smaller to the infrequent larger event rates, and an improved understanding of its properties and meaning is crucial to advance future seismic hazard assessment. Recent years have offered exciting new insights, according to which the observed natural b-value variability can be related to physical properties of the crust, in particular its stress distribution, such as has been suggested from lab experiments for decades.

We invite b-value related contributions from all scales - laboratory, induced and natural seismicity - addressing variability or stability in space and through time. We would like to discuss statistical requirements, appropriate techniques and uncertainty treatment; we are particularly interested in approaches of physical interpretation - (what) can we learn from b-value analysis about the physics of the crust and spatiotemporal earthquake potential? We also invite studies from different backgrounds that face similar analysis challenges or reveal related characteristics, such as strong along fault heterogeneity - do they offer new correlation prospects with b? Or what about b-values in the physical earthquake simulator world?

We aim for a forum to discuss the state-of-the-art in b-value analysis and its impact and outline future challenges and opportunities.

Conveners: Thessa Tormann (thessa.tormann@sed.ethz.ch), Max Wyss (wyss.adh@gmail.com) and Jeanne Hardebeck (jhardebeck@usgs.gov)

A Decade of Great Subduction Earthquakes - What Have We Learned From Their Ground-Motions?

Of the nine largest subduction zone earthquakes documented since 1900, four have occurred in the last 10 years, including; 2004 Sumatra-Andaman Islands and 2005 Nias, Indonesia; 2010 Maule, Chile, and; 2011 Tohoku, Japan. Many of these earthquakes, together with their aftershocks and a host of "smaller" - but equally important - independent earthquakes have generated large databases of digital ground-motion recordings and macroseismic intensities.

This session will discuss subduction zone ground-motion observations (both instrumental and macroseismic) for modeling hazard and risk globally. We seek contributions that address a range of questions, including: Can ground-motion models developed from one global database (e.g., Japan) be translated to another region (e.g., Alaska or Cascadia)? Are current magnitude scaling models appropriate for Great earthquakes? How do we model the ground-motion uncertainties? What macroseismic effects are commonly observed from these events? How can we leverage of modern and historical macroseismic data to inform ground-motion model development for hazard assessments? Are global monitoring seismic networks sufficient for monitoring large subduction events? How can we use this information to mitigate the potential impacts of future large subduction earthquakes?

Conveners: Trevor Allen (tallen@nrcan.gc.ca) and Gail Atkinson (gmatkinson@aol.com)

Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales

This session will cover new developments in seismic imaging and monitoring, from the sub-meter-scale in engineering applications for controlling civil structures to the meter-scale in near-surface seismology, up to the kilometer-scale of shallow crustal seismology. Contributions dealing with controlled-source continuous or repeated observations to detect temporal variations of seismic velocity or other properties are especially welcome. We invite submissions relevant to theoretical and practical aspects using both active and passive seismic data, methodological studies, and studies aimed at developing new instrumentation. We aim to highlight progress of imaging and surveillance studies and related research in real-time seismic hazard monitoring.

Conveners: Marco Pilz (pilz@gfz-potsdam.de) and Nori Nakata (nnakata@stanford.edu)

Advances in Understanding Earthquake Hazard in Central and Eastern North America

About twenty M4 to M5.8 earthquakes have occurred since 2010 in the intraplate region of Central and Eastern North America. Most of these events were well recorded by ANSS and USArray seismographs and provide data that can contribute to reducing uncertainties in seismic hazard assessment. From recordings of these events we seek contributions providing insights into seismic source characteristics, aftershock behavior, attenuation, site response, crustal structure relative to characterization of seismic and aseismic regions, and building damage. All aspects of studies related to the 2011 M5.8 Mineral, Virginia earthquake are of particular interest.

Conveners: Robert Williams (rawilliams@usgs.gov), Mitch Withers (mwithers@memphis.edu), William Stephenson (wstephens@usgs.gov) and John Ebel (john.ebel@bc.edu)

Alaska Update of the USGS National Seismic Hazard Maps

The United States Geological Survey (USGS) plans to update the Alaska portion of the U.S. National Seismic Hazard Maps to produce science-based products that will be considered for inclusion in future building codes, risk assessments, and other public policy applications. These seismic hazard maps are based on our assessment of the "best available science" at the time of the update, and incorporate a broad range of scientific input models and parameters. We invite papers discussing new geologic and geophysical information on Alaska seismic sources (faults and seismicity) and ground motion models. In particular we are interested in new paleoseismic fault studies, geodetic and geologic combined inversions of fault slip rates, and ground motion models for subduction and crustal sources.

Conveners: Peter Haeussler (pheuslr@usgs.gov), John Anderson (jga@seismo.unr.edu) and Mark Petersen (mpeterson@usgs.gov)

Citizen Seismology: Citizens Helping Science Helping Citizens

There is a growing trend across scientific disciplines for citizens to aid scientific research and monitoring. In seismology, citizens now contribute both actively and passively to the collection and analysis of seismic data. These efforts include documenting macroseismic effects on a scale not imaginable before the advent of the Internet, contributing to early detection of significant earthquakes, and hosting of seismometers of various types. Citizen seismology clearly offers enormous potential to not only contribute to scientific research but also to push scientists to better understand and respond to public demands and expectations after natural disasters. In this session we invite contributions that focus on quantitative analysis of macroseismic data from both historical and instrumental earthquakes as well as papers that cover technical aspects of citizen science, ways to better engage with citizens,and other applications.

Conveners: Paul Earle (pearle@usgs.gov), Susan Hough (hough@usgs.gov) and Gail Atkinson (gmatkinson@aol.com)

Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks

Temporary and long-term seismic networks reach all corners of the globe. Over the last decade, the increased interest in glacier and polar seismology concerning climate research, and more recently, the move of USArray to Alaska, have raised expectations that temporary seismic stations will operate continuously in these extreme environments. Polar climates pose particular challenges to temporary and long-term networks and the instrumentation that is deployed. Cold temperatures, snow cover, freeze-thaw cycles and short daylight hours challenge the operational capabilities of these remote stations. Logistic constraints limit the size of deployable, off-the-grid power systems, and limited winter access dictates that equipment must operate for many months or years without maintenance visits, some blind even of state of health information.

This session will focus on new developments in cold-climate seismic deployments, including enclosures, power systems, telemetry, instrumentation, and logistics.

Conveners: Bruce Beaudoin (bruce@passcal.nmt.edu) and Christopher Bruton (cpbruton@alaska.edu)

Deciphering the Earthquake and Tsunami History of Subduction Zones

Recent great earthquakes and their accompanying devastating tsunamis in Sumatra, Chile, and Japan highlight the need for subduction-zone histories that span the hundreds to thousands of years needed to sample the greatest events. Few instrumental measurements cover more than a fraction of the cycle of interplate strain accumulation and release at active subduction margins. Even on the few coasts with extensive historical archives, records are too short or incomplete to fully reconstruct the history of the greatest earthquakes and highest tsunamis. Without accurate reconstructions spanning multiple earthquake cycles, there is little hope of understanding the variables that control how megathrust ruptures nucleate and extend along subduction zones, how the highest tsunamis are generated and dispersed across ocean basins, and in assessing the hazards from these great events. The century to millennia-long recurrence times of these events dictates the use of an array of interdisciplinary techniques from, for example, the fields of stratigraphy, geomorphology, dating, paleontology, oceanography, and history, to determine the timing and characteristics of past events. This session will explore recent developments in reconstructing the histories of large earthquakes and tsunamis on active subduction margins worldwide. We especially encourage presentations comparing and contrasting earthquake and tsunami behavior at different subduction zones, presentations integrating multiple techniques to characterize earthquake and tsunami behavior, and descriptions of new and innovative methods of investigation.

Conveners: Marco Cisternas (marco.cisternas@ucv.cl), Lisa Ely (ely@cwu.edu), Ed Garrett (edmund.garrett@durham.ac.uk), Daniel Melnick (Daniel.Melnick@geo.uni-potsdam.de), Alan Nelson (anelson@usgs.gov) and Robert Wesson (rwesson@wispertel.net)

Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications

The 2014 National Seismic Hazard Maps (NSHMs) produced by the United States Geological Survey (USGS) incorporate significant changes in the earthquake catalog, source models, and ground motion models. These seismic hazard maps are based on the USGS' assessment of the "best available science" at the time of the update, and incorporate a broad range of scientific input models contributed by the seismological research community. The NSHMs are used to produce science-based products that will be considered for inclusion in future building codes, risk assessments, and other public policy applications. We invite papers that discuss major changes to the maps or to the input data and models (e.g., catalog, source models, ground motion models) since 2008; or discuss improvements in data, methods, and models that could be used in future maps. Papers that discuss the impact of the 2014 NSHMs on design maps and future building codes are encouraged.

Conveners: Sanaz Rezaeian (srezaeian@usgs.gov), Christine Goulet (goulet@berkeley.edu), John Anderson (jga@seismo.unr.edu) and Mark Petersen (mpetersen@usgs.gov)

Development of Next Generation Field Methods for Portable Broadband Seismic Arrays

Researchers have started to deploy the next generation of directly buriable broadband seismic sensors after years of building vaults to protect arguably observatory-grade sensors that were neither rugged nor water resistant, using shallow simple vaults that limited their noise performance. The debate of whether to chase the final 2-10 dB of noise floor in shallow vaults has shifted to the question of what are the signal-to-noise ratios required to collect enough events that will allow more successful deployments with limited logistics and minimal budgets? This session will present techniques and

developments to enable broadband seismology to increase the number of successfully deployed stations with decreasing logistical budget requirements including use of other types of shorter-period sensors in mixed-mode arrays.

Conveners: Timothy Parker (tparker@passcal.nmt.edu) and David E. Hawthorn (dh109@leicester.ac.uk)

Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships Among Seismic Rupture, Transient Slip, and Steady Creep

The release of elastic energy at subduction zone faults can result in intense ground shaking over broad regions and sea floor displacement that generates immense tsunamis. Tectonic tremor and/or slow slip, commonly observed between the seismogenic zone and down-dip stable sliding, represents an intermediate mechanism for faults to accommodate plate convergence. Yet the relative location of these different slip behaviors varies among subduction zones both along-strike and along-dip. Additionally, some subduction zones accommodate strain through aseismic stable sliding within the depth range where large earthquakes are expected to occur. Why such variability exists (e.g., frictional, rheological properties, material heterogeneity, variations in fluid pressure) and how it affects great earthquakes (e.g., up-dip or down-dip extent of seismic rupture, incomplete inter-seismic coupling) is poorly understood. It also remains unclear whether these diverse mechanisms are consistent over time or what role they play in the earthquake cycle. The objective of this session is to showcase the current understanding on these topics, and we seek to combine a wide range of abstracts that utilize observations, theory, or modeling with aspects from seismology, geodesy, lab experiments, and field observations.

Conveners: Harmony V. Colella (colellhv@miamioh.edu), Emily C. Roland (eroland@usgs.gov) and Aaron G. Wech (awech@usgs.gov)

Earthquake Physics and Interaction

This session highlights recent advances in earthquake physics and the interrelationships between earthquakes in a particular region. Topics include earthquake clustering, time-dependent forecasting, scaling relationships, stress drop studies, and others.

Effects of Topography and Surface Loads on Earthquakes and Faulting

Topographic features can produce significant stress in the lithosphere. These topographic stresses can be on the order of inferred stress drops in earthquakes, raising the possibility that they may affect the earthquake processes. In the upper crust, the topographic stresses can be quite heterogeneous, resulting in stress heterogeneities of both fault shear and normal stresses even if the background tectonic stress is relatively smooth. Dynamic earthquake simulations have shown that stress heterogeneities on the order of several MPa or more have a strong effect on the earthquake rupture process. Additionally, flexure and isostatic rebound due to changes in water, ice or sediment loads on the Earth's surface can affect fault behavior over many earthquake cycles, and in some cases may trigger earthquakes on relatively short timescales.

We call for theoretical or empirical research on the interactions of topography and surface loads with earthquake behavior. We particularly welcome submissions addressing the following broad topics: Models of dynamic earthquake rupture with heterogeneous pre-earthquake fault normal and shear stress; Constraints on the stress evolution throughout an earthquake, including both stress drop and final post-earthquake stress; relationship of topographic stresses and rupture in an individual earthquake; Relationship between topography and location or style of faulting; Modulation of fault activity due to changes in surface loads; and Measurements and quantitative estimates of stresses near faults.

Conveners: Richard Styron (richard.h.styron@gmail.com) and Eric Hetland (ehetland@umich.edu)

Emergence of Continuously Recording Very Large Array Capabilities in Seismology

Enhanced recovery, injection well monitoring, microseismic monitoring, energy exploration, and reservoir characterization/monitoring are driving dramatic new commercial-sector seismic instrument development and analysis techniques in the energy industry. The associated multichannel capabilities are up to orders of magnitude greater than have been available to non-industry-aligned academic seismology. This expansion of monitoring and imaging scope has also produced renewed emphasis on the use of broader-band instrumentation at very large network/array scales. This session will encompass both the diverse scientific/industry opportunities associated with the deployment and analysis of very large numbers of seismographs, and opportunities for associated novel collaborations within the greater seismological and Earth science community.

Conveners: Rick Aster (aster@ees.nmt.edu) and James Gridley (james.gridley@iris.edu)

Explosive Source Characterization

In this session, we investigate the coupling of explosive energy to the radiated seismic wave field. Integration of detailed site setting, material characterization and modeling efforts for understanding explosive sources is critical for nuclear test monitoring and verification. In order to relate near field explosive source phenomenology with far-field observations in areas where characterization data may not exist, well-constrained input and validation from materials testing, structural analysis, field observations, overhead imagery, subsurface feature detection, first-principle calculations, and source-to-receiver modeling are required. These approaches must then be translated into useful, transportable methods for the verification community to characterize the source and quantify uncertainties. We invite contributions from all research focus areas and technologies that meld efforts described above.

Conveners: Catherine Snelson (snelsocm@nv.doe.gov), Christopher Bradley (cbradley@lanl.gov), Sean Ford (ford17@llnl.gov) and Kyle Jones (krjones@sandia.gov)

Fault Structure, Heterogeneity, and Implications for Rupture Dynamics

Faults are complex zones of highly deformed rock containing hydro-mechanical heterogeneities from the grain to plate boundary scale. These heterogeneities influence frictional properties of faults and control the dynamics of slip instabilities from episodic tremor and slow slip to large earthquake ruptures. Rupture nucleation, propagation and arrest may be affected by variations in intrinsic fault characteristics, for example, fault hydrology, geometry and structure. While fault structure has been studied extensively on exhumed faults much remains unknown about fault structure at depth and its interplay with earthquake ruptures. Can fault heterogeneity limit the length of earthquake ruptures and control nucleation points of large earthquakes? Can fault heterogeneity explain the large diversity of slip behavior (from exotic slow events to large earthquakes) observed along faults? How do ruptures depend on faults characteristics, e.g., roughness, pore pressure and frictional properties? How does deformation localize within faults and is the degree of localization a function of fault lithology and age? How does fault heterogeneity evolve with successive rupture events? How are off-fault damage zones created? What is the contribution of dynamically vs. statically created damage? How is fault heterogeneity connected to the creation of fore and aftershocks? To encourage an exchange on some of these questions, we solicit contributions from observational, numerical and experimental studies of fault structure, heterogeneity and implications for earthquake ruptures.

Conveners: Thomas H. W. Goebel (tgoebel@gps.caltech.edu), Thibault Candela (txc32@psu.edu) and Heather Savage (hsavage@ldeo.columbia.edu)

Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario - Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation

In recent years, the study of tsunami hazard has evolved from the traditional numerical modeling environment to include loss estimates and mitigation measures, partly due to the large tsunami disasters of the last decade. For instance, the USGS SAFRR scenario for a large Alaskan tsunami's impact in California rolled out in 2013/2014 to coincide with the 50th anniversary of the 1964 Alaska earthquake and tsunami. This session brings together all the different facets of tsunami hazard analysis, from advances in source characterization, propagation and runup modeling to loss estimation and mitigation measures. The session will include several presentations on the SAFRR scenario, and we invite contributions in the broad range of tsunami research including tsunami source characterization in both deterministic and probabilistic framework, new techniques and technologies in numerical analysis and hazard mapping. Studies in the field of tsunami preparedness of the population, perception of risk, human behavior during the event and effectiveness of tsunami warnings are welcomed. We expect the contributed papers to help us better understand the missing pieces in the existing tsunami mitigation programs and improve resilience of coastal communities to tsunami hazards.

Conveners: Elena Suleimani (elena@gi.alaska.edu), Stephanie Ross (sross@usgs.gov), Hong Kie Thio (hong.kie.thio@urs.com) and Dmitry Nicolsky (djnicolsky@alaska.edu)

From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering

Seismologists and engineers with the capability to understand the scientific and technical features of physical and numerical models including the physics of earthquake source, wave propagation effects, site specific ground motion predictions and seismic vulnerability of structures, are key professional figures within the framework of seismic risk assessment and mitigation studies. Building these professional skills requires seamless cooperative efforts between earthquake scientists and earthquake engineers. This expertise is routinely employed and optimized by a number of governmental, academic and industrial stakeholders. With the aim of gathering and promoting the discussion amongst the aforementioned scientists and engineers, in this session we welcome innovative studies on the topics mentioned above, with strong emphasis placed on practical applications, characterized by a successful integration of seismological and engineering advancements, tailored to the mitigation of seismic risk.

Conveners: Luis A. Dalguer (dalguer@sed.ethz.ch), Carlo Cauzzi (carlo.cauzzi@sed.ethz.ch), Aysegul Askan (aaskan@metu.edu.tr) and Philippe Gueguen (philippe.gueguen@ujf-grenoble.fr)

Geometric Complexities Along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution

Major, active strike-slip fault zones around the world often have discrete zones of deformation and elevated seismicity focused around restraining bends and other geometric complexities of the trace of the main strike-slip fault. Alaska contains two world-class examples of extreme deformation and complex seismicity patterns along major strike-slip fault systems - the Mount McKinley restraining bend of the Denali fault, and the Alaskan syntaxis associated with the Fairweather fault. With this meeting having these dramatic examples as a backdrop, we seek contributions that provide global insight into focused zones of deformation along strike-slip faults and their influence on earthquake rupture and recurrence behavior, fault system evolution and the differences in seismic hazards between the primary strike-slip fault and subsidiary faults. We welcome contributions from seismology, paleoseismology, thermochronology, structural geology, geodesy, and analogue/numerical modeling, exploring both theoretical studies and field-based examinations of restraining bends around the world, including (but not limited to) the well-studied examples from the San Andreas fault system, the major fault systems of central Asia and South/Central America, the Dead Sea fault, the North Anatolian fault, and the Alpine fault.

Conveners: Sean P. Bemis (sean.bemis@uky.edu), Jeff Benowitz (jbenowitz@alaska.edu) and Michele Cooke (cooke@geo.umass.edu)

Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)

This session invites presentations about large and great earthquakes in convergent zones, especially those events that have significant slip on the shallow portion of the megathrust close to the trench. These types of seismic events, such as the 2011 Tohoku-oki earthquake, have the potential for producing very large tsunamis, as well as strong shaking, and the potential for triggering widespread landslides and liquefaction. We invite papers on to recent seismic and geodetic observations characterizing sources, constraints on the controlling structures and material properties, and modeling studies related to great subduction zone earthquakes.

Conveners: Jim Mori (Mori@eqh.dpri.kyoto-u.ac.jp), David Wald (wald@usgs.gov) and Emily C. Roland (eroland@usgs.gov)

Induced Seismicity

Recent damaging earthquakes in Oklahoma, Colorado, and Arkansas have renewed interest in induced seismicity. Across the central and eastern United States, the seismicity rate has doubled over the past 11 years. This rate change can largely be attributed to earthquakes induced by fluid injection associated with oil and gas production. Given the occurrence of damaging earthquakes and the large increase in seismicity rate observed in the United States, it is of critical importance that induced earthquakes are better understood such that their hazards may be mitigated. Topics of interest to address these issues include: the causes of fluid-injection induced earthquakes; methods to distinguish natural and induced earthquakes; why some wells trigger earthquakes, but the vast majority of wells do not; how fluid-injection induced earthquakes may be controlled; and how to estimate the hazard associated with already developed and new fluid injection fields. We invite papers on all forms of induced seismicity but particularly those associated with waste water-injection, geothermal production, carbon sequestration, and hydraulic fracturing. Papers from industry are particularly welcome to better inform the research community on the state of knowledge and practices within the community. As part of this session, a roundtable discussion will be held to discuss (1) the factors influencing induced seismicity, (2) the uncertainties in characterizing induced seismicity, (3) strategies to control induced seismicity, and (4) methods to characterize the earthquake hazards associated with fluid injection.

Conveners: Ivan Wong (ivan.wong@urs.com), Justin Rubinstein (jrubinstein@usgs.gov) and Thomas Braun (thomas.braun@ingv.it)

Large and Damaging Earthquakes of 2013/2014

Large earthquakes have continued to garner global attention in 2013. Significant events have struck Iran (Khash, April 2013, Mw7.7); China (Lushan, April 2013, Mw6.6); Russia (Okhotsk, May 2013, Mw8.3); New Zealand (Blenheim, August 2013, two Mw 6.5 earthquakes); Pakistan (Awaran, September 2013, Mw7.7); and the Philippines (Bohol, October 2013, Mw7.1), all in the past half-year. Further large and damaging events may also occur over the following six months.

Studies of these earthquakes are important not only from a societal perspective - several of these events each caused hundreds of fatalities, and significant economic losses - but also seismologically - the Sea of Okhotsk earthquake was the largest deep earthquake ever recorded, and the Pakistan earthquake was another example of a large continental event involving complex slip on multiple fault structures. We welcome analyses of these earthquakes, from teleseismic to regional studies using seismic data, to co- and post-seismic GPS and InSAR analyses, to studies of the societal and economic impact of such events. Research that tackles event characterization from a multi-disciplinary approach is particularly encouraged.

Conveners: Gavin Hayes (ghayes@usgs.gov), Thorne Lay (tlay@ucsc.edu), Harley Benz (benz@usgs.gov) and Charles Ammon (cja12@psu.edu)

Merging Paths: Earthquake Simulations and Engineering Applications

Recent and continuing efforts in broadband hybrid and deterministic modeling of earthquake processes indicate that we are approaching a junction where physics-based ground motion simulation techniques can be integrated with seismic hazard analysis, risk and loss assessment studies, engineering analysis and design. This session invites participants to contribute their work in the broader area of earthquake modeling and simulation (coupled) with engineering applications. Topics of interest include: high-frequency ground motion simulation; integrated earthquake simulation, end-to-end and/or rupture-to-rafters simulation; integration of nonlinear soil, surface topography and other site effects in simulation; local and regional simulations including soil-structure and site-city interaction effects; structural systems modeling, analysis and design using simulation synthetics as input; earthquake simulations coupled with GIS data; loss and damage assessment based on synthetic datasets; use of ground motion simulations for evacuation plans and emergency response.

Conveners: Ricardo Taborda (ricardo.taborda@memphis.edu), Aysegul Askan (aaskan@metu.edu.tr) and Tsuyoshi Ichimura (ichimura@eri.u-tokyo.ac.jp)

Monitoring Dynamic Changes at Active Volcanoes and Fault Zones

Emerging time-lapse geophysical methods offer the opportunity to observe active geologic systems as they evolve. For example, examination of the coda of repeating earthquakes and ambient seismic wavefields have allowed for the detection of small temporal changes in velocity at active volcanoes and fault zones. Other recently discovered observables show promise for being even more sensitive measures of small changes. These dynamic methods of observation can provide insight into changing

fault zone properties during the seismic cycle or the evolution of a volcanic eruption. In this session, we welcome studies that employ time-lapse geophysical methods to monitor active geologic systems. What can such methods tell us about these systems and how can they be efficiently transferred into tools for routine monitoring?

Conveners: Ninfa Bennington (ninfa@geology.wisc.edu), Matt Haney (mhaney@usgs.gov) and Silvio de Angelis (silvioda@liverpool.ac.uk)

Near-Field Seismoacoustics of Natural and Man Made Explosions

Multiparameter observations (e. g., seismic, acoustic, video, etc.) of natural and man made explosions have the potential to provide important details of source time functions and coupling of seismoacoustic waves. For example, a series of recent studies have observed signatures of rapid ground deformation, distortions due to topographic effects, production of nonlinear acoustic waves, and complex seismoacoustic partitioning during explosions. Understanding these relationships is important for characterizing geophysical phenomena in the atmosphere and the solid earth. Such detailed knowledge is also critical in volcano and nuclear explosion monitoring. We encourage contributions that describe extensions of our current seismoacoustic monitoring capabilities with innovative technologies, network configurations, and observational methods.

Conveners: Daniel Bowman (daniel.bowman@unc.edu), Keehoon Kim (keehoon@email.unc.edu) and Jonathan Lees (jonathan.lees@unc.edu)

Network Operations and Data Centers

This session consists of papers on new developments in seismic and GPS networks and data centers. These include reports on new types of instrumentation, upgrades of existing seismic networks, and data processing. Great data is of no value unless it can get to the user. The session also includes new developments in serving data to the earthquake community.

New Directions in PSHA: Ins, Outs, and Uncertainty

In light of recent advances in earthquake science, data, and computational resources, probabilistic seismic hazard analyses (PSHAs) have increased in complexity. Such complexity manifests as larger logic trees, more sophisticated data-integration techniques, better understanding of input data uncertainties, and the computational capacity to undertake high-resolution simulations (e.g., CyberShake) and inversions for earthquake rate models (e.g. UCERF3). We invite papers on topics that include uncertainty analysis in PSHA, new approaches to gridded, area, and finite-fault source representations, logic-tree analysis and trimming, deaggregation, site-specific methodologies, computational algorithms, simulation based methods, urban hazard maps, new source and ground motion models, and other research or approaches related to PSHA.

Conveners: Peter Powers (pmpowers@usgs.gov), Morgan Moschetti (mmoschetti@usgs.gov) and Ned Field (field@usgs.gov)

New Insights into Ground Failure as an Urban Earthquake Hazard

The 1964 Alaska Earthquake was significant for many reasons - including extensive observations of ground failure. As we celebrate the 50th anniversary, we will look at recent earthquakes, including the 2011 Tohoku earthquake and the 2010-2011 Christchurch Earthquake that have provided new datasets on ground failures. These new datasets facilitate research that improves ground failure models and provides insight into ground failure mechanisms. This session will highlight developments in ground failure models with special focus on urban earthquake hazard. Among the ground failure hazards to be addressed are surface rupture, liquefaction and landsliding.

Conveners: Laurie Baise (laurie.baise@tufts.edu) and Keith Knudsen (kknudsen@usgs.gov)

Pillars of Simulation: Seismic Velocity and Material Models

Various research and application areas in geophysics, seismology and engineering are strongly dependent on the seismic velocity and material models used in simulation today. While much progress has been done over the last decades in advancing such models, our knowledge about the geology and structure of the crust and its sedimentary basins and the near-surface geotechnical layers, as well as our modeling approaches to represent the mechanical properties of materials beneath the surface are somewhat limited. This session solicits contributions in the broad area of seismic velocity and material models and their application in earthquake (source and ground-motion) simulation. Topics of particular interest include but are not limited to: development of new and improvement of currently available community velocity models, description of velocity models software, discrete representation of velocity models used for simulation, verification and validation of velocity models, full waveform tomography and inversion, attenuation and/or quality factor rules, visco-elastic material models, off-fault and near-surface plasticity, initial stress conditions and elasto-visco-plastic models in simulations including material nonlinear behavior, integration of geotechnical data, and representation of heterogeneous media.

Conveners: Ricardo Taborda (ricardo.taborda@memphis.edu), Po Chen (pchen@uwyo.edu) and En-Jui Lee (elee8@uwyo.edu)

Recent Advances and Findings in Earthquake Geology and Paleoseismology

Characterizations of the timing, recurrence, displacement, and rupture extent of recent surface-faulting earthquakes provide key inputs for earthquake-probability forecasts and seismic-hazard assessments. This session will highlight recent advances in the fields of earthquake geology and paleoseismology from investigations of Quaternary-active faults. We invite abstracts that present 1) paleoseismic earthquake histories and improved estimates of earthquake recurrence, fault slip rate, and rupture extent; 2) techniques for investigating surface ruptures, such as remote sensing of surface deformation and offset (e.g.,

InSAR, GPS, and pixel tracking); and 3) objective methods of synthesizing multiple paleoseismic datasets. The goal of this session is to critically evaluate how detailed fault and earthquake characterizations inform our understanding of seismic hazard.

Conveners: Scott Bennett (sekbennett@usgs.gov) and Christopher DuRoss (christopherduross@utah.gov)

Recent Advances in Ground Motions Simulation Methods and Their Validation

This session is targeted to highlight recent advances in the development and validation of ground motion simulation methods. Topics of interest include: formulation of new or updated simulation methods with description of parameterizations of the source, path and/or (nonlinear) site effects; models including small-scale heterogeneity in the source or surrounding medium or incorporating 3D complexity of the medium and/or mountain topography; methods for better constraining input; sensitivity of methods to ranges of plausible input parameters; and quantification of uncertainty in simulated ground motions. We also invite case histories comparing ground motions from various simulation techniques, as well as calibration and validation of methods against recordings and/or ground motion prediction equations. The session is open to a wide range of simulation methodologies, including deterministic and stochastic models of wave propagation, with stochastic, kinematic or dynamic models of the source description.

Conveners: Christine Goulet (goulet@berkeley.edu) and Kim B. Olsen (kbolsen@mail.sdsu.edu)

Seismic Imaging as USArray Moves to Alaska (IRIS/Seismological Society of America Joint Session)

In 2014 the USArray Transportable Array will begin deploying in Alaska, after ten years successfully crossing the entire lower-48 states. The arrival of the Transportable Array in Alaska presents an unprecedented opportunity to image one of the most seismically and tectonically active regions of the world. We encourage contributions highlighting results achieved already with USArray data or which provide the context and framework for discoveries to come. The goals of the session are to identify opportunities for characterizing structures of the crust (including basins and volcanoes), slab, and mantle using complementary data sets. Example data sets include onshore and offshore data, active and passive seismic data, ambient noise and earthquake data (local or teleseismic), and potential field data. We encourage submissions featuring techniques that harness large emerging data sets and modern computational methods.

Conveners: Carene Larmat (carene@lanl.gov), Frank Vernon (flvernon@ucsd.edu) and Bob Woodward (woodward@iris.edu) and Lindsay Worthington (lworthington@unm.edu)

Seismic Location and Processing Techniques

Modern earthquake location and monitoring techniques have revolutionized seismology, allowing better images of fault structure, stress, and time-dependent frictional properties. This session explores new techniques and results in this important seismological field.

Site Response: From Site-Specific Analyses to Predictive Models Around the Globe

We invite contributions that fall within the broad category of site response analysis, including topics from advances in fundamental soil behavior modeling to simplified methods for mapping site response at the national and global scales. Site response has been a hotly debated topic between engineers and seismologists for decades. In the recent years, the two communities have reached consensus on the nonlinear nature and importance of site response as a constituent of ground motion predictions and seismic hazard assessment; faced with the ever increasing amount of recorded evidence in statistical studies, or pushing the envelope of high frequency ground motion simulations, many seismologists currently account for nonlinear soil effects in their studies. Thus, the classic debate has shifted towards more subtle and interconnected issues, such as the use of the average shear-wave velocity to 30 m (Vs30), empirical vs. theoretical modeling approaches, time-domain vs. spectral analyses, and the accuracy of fundamental modeling assumptions. Although different approaches can be cast as controversies, it is useful to see them as solutions to different problems rather than competing solutions to the same problem. For example, although a nonlinear time-domain analysis more accurately accounts for soil behavior than statistical correlations with Vs30, the latter approach may be the only option available for applications at sites where dynamic soil properties are unavailable. In this context, we encourage submissions to focus on the motivations behind their modeling choices, and to discuss the applications and scales where their approach is expected to be most beneficial.

Conveners: Eric Thompson (ethompson@mail.sdsu.edu) and Dominic Assimaki (dominic@gatech.edu)

Topics in Seismology: Hazards

A primary incentive to understanding earthquakes is in evaluating the hazard. This session includes presentations on a diverse array of hazard analysis, from precariously balanced rocks, to nuclear plants, to the L'Aquilla trial, and the utility of response spectra.

Topics in Seismology: Processes

Processes that lead to seismicity are diverse and varied from common slip of rocks along faults to ice quakes to fluid-induced seismicity. This session presents research on processes leading to seismicity.

Topics in Seismology: Regional Seismicity and Tectonics

A better evaluation and understanding of earthquake hazards can only come from regional studies of seismicity and active deformation. This session presents research on regional seismicity from around the globe.

Tracking Fluid Movement in Volcanic Systems

Seismology has long been the primary means through which to study and monitor the movement of magma and other fluids in active volcanic systems. However, despite decades of seismic monitoring at volcanoes, the ascent of magma and the circulation of fluids within volcanic systems, and how these phenomena are reflected in geophysical signals, remain poorly understood.

In recent decades, improvements in instrumentation and processing techniques have led to the development of additional geophysical tools capable of tracking fluid movement, including infrasound, high-rate GPS, InSAR and gravity. These tools, often used in concert with seismological techniques, have brought forth many new insights that were previously unknown. We seek submissions highlighting interdisciplinary geophysical monitoring and study of fluid movement in active volcanoes and geothermal systems. We encourage contributions that emphasize advances in numerical modeling, feature new instrumentation or analytical methods, and/or provide new insights into the physical processes controlling fluid movement.

Conveners: John Lyons (jlyons@usgs.gov), Helena Buurman (helena@gi.alaska.edu), Diana Roman (droman@dtm.ciw.edu) and David Fee (dfee@gi.alaska.edu)

JOYNER LECTURE

David Boore will deliver this year's Joyner Lecture: "Ground-Motion Prediction Equations: Past, Present and Future." David is a Geophysicist with the United States Geological Survey in Menlo Park, California. The Joyner Lecture was established to honor William B. Joyner's pursuit of bringing earthquake seismology and earthquake engineering closer together so as to provide for a safer society.

WORKSHOP

Pre-Meeting Media Workshop: Communicating with Non-Technical Audiences

Tuesday, 29 April 2014, 10:00 AM-4:00 PM (the day *before* the start of the regular meeting program).

SSA is offering attendees an opportunity for practical, hands-on training in communicating technical information for a lay audience. Learn the foundation of working with the media - crafting a simple message that's memorable. The majority of the workshop, scheduled for 10 AM-4 PM, will involve on-camera work and small group exercises. Each trainee will participate in at least one mock interview.

Nan Broadbent will facilitate the workshop. She is the press liaison for SSA, promoting the Annual Meeting and journals to the media. Prior to SSA, Nan worked in Washington, D.C., where she focused on research communications. She served as communications director for the journal *Science* and the American Association for the Advancement of Science. She conceived of and created EurekAlert!, which is a tool widely used by science reporters and public relations officers.

GOVERNMENT RELATIONS WORKSHOP

How Congress Works and How You Can Work Congress

Wednesday, 30 April and Thursday, 1 May 7:30–8:30 AM

In this contentious legislative environment, with declining budgets and sequestration, every scientist needs to know how to make the best case for their science. Come for an informative session and find out about the inner workings of the US Congress, how laws are made, and how to become an effective advocate for science.

Elizabeth Duffy, President of the Federal Affairs Office in Washington, D.C. and government affairs coordinator for SSA, will lead this session. Elizabeth will bring over 20 years of business, political and advocacy experience to show you how to best impact legislation in Congress, how to establish productive relationships with elected officials and their offices, and how to speak to representatives to get your message heard.

FIELD TRIP

The 1964 Earthquake, Tsunamis, Paleoseismology, and Subduction Processes in Southcentral Alaska

Leaders: Peter Haeussler (USGS, Anchorage) and Ian Shennan (University of Durham)

The field trip will leave at 8:30 AM on Saturday, 03 May 2014 (the day following the close of the regular meeting program) from the Anchorage Hilton lobby and return at approximately 6:30 PM. Please do not plan to catch a flight that evening as we cannot guarantee the bus will return on schedule.

This one-day field trip will travel along beautiful Turnagain Arm from Anchorage to Whittier and back - 120 miles, round trip. The field trip will feature stops that highlight effects and lessons learned from the 1964 M9.2 Great Alaska earthquake. The first stop will be at the famous Turnagain Heights landslide, which slid up to 610 m. The next stop will be in rocks of the Mesozoic accretionary complex, to show processes that occurred at seismogenic depths and discuss the long-term tectonic history of the region. The next stop will be at the Girdwood flats. This is a world-class paleoseismic site, which has excellent exposures of the stratigraphy of the 1964 earthquake and beautiful views of the ghost forest, which developed after the forest tree roots dropped into the intertidal zone. The next stop will be at Portage Lake, to discuss the history of the Little Ice Age in the region. The bus will then travel thru a unique 4 km long tunnel to the community of Whittier (population 150), at the western edge of Prince William Sound. Here, submarine landslide processes will be discussed that led to local tsunami generation and loss of 13 lives in the 1964 earthquake.

It is MANDATORY for people to have calf height rubber boots at the Girdwood stop. This is not a mere suggestion. They can be purchased at the Army Navy Store, which is in walking distance from the Egan Center. People may get muddy. Participants should bring rain gear as there is a reasonable chance of rain and a high chance of wind. Expect temperatures from the 40s to the 60s.

MEETING INFORMATION

Registration

Online Registration at http://www.seismosoc.org/meetings/2014/reg/. Early registration discounts apply until March 28. Online registration ends on April 18.

Preliminary Schedule
Events will be held at the Egan Center in Downtown Anchorage, Alaska.

Tuesday, 29 April
Board of Directors Meeting (9:30 AM–5:00 PM)
Media Workshop (10:00 AM–4:00 PM)
Speaker Ready Room (3:00 PM–7:00 PM)
Registration (3:00 PM–8:00 PM)
Icebreaker Reception (6:00 PM–8:00 PM)

Wednesday, 30 April
Government Relations Workshop (7:30 AM–8:25 AM)
Speaker Ready Room (7:30 AM–6:00 PM)
Technical Sessions (8:30 AM–6:00 PM)
Annual Luncheon (12:00 PM–2:00 PM)
Student Reception (5:45 PM–7:30 PM)
Early Career Reception (5:45 PM–7:30 PM)

Thursday, 1 May
Government Relations Workshop (7:30 AM–8:25 AM)
Speaker Ready Room (7:30 AM–6:00 PM)
Technical Sessions (8:30 AM–6:00 PM)
Lunch (12:00 PM–1:00 PM)
Joyner Lecture (5:15 PM–6:15 PM)
Reception (6:15 PM–7:30 PM)

Friday, 2 May
Speaker Ready Room (7:30 AM–4:30 PM)
Technical Sessions (8:30 AM–5:00 PM)
Lunch (12:00 PM–1:00 PM)

Saturday, 3 May
Field Trip

This schedule is subject to change.

HOTEL AND TRAVEL INFORMATION

The conference will be held at the **Egan Civic and Convention Center** in downtown **Anchorage**. SSA will have the entire center for our conference.

The conference hotel is the **Hilton Anchorage**. It is the closest hotel to the Egan Center, about 1½ blocks away. SSA has negotiated an excellent room rate.

Please visit http://www.seismosoc.org/meetings/2014/hotel.php for links to the hotel registration, lists of things to do in Anchorage, and visa information.

INFORMATION FOR EXHIBITORS AND SPONSORS

Organizations wishing to register as exhibitors can do so online at http://www.seismosoc.org/meetings/2014/exhibit/. Organizations wishing to sponsor the SSA 2014 meeting can do so online at http://www.seismosoc.meetings/2014/sponsor/.

Overview of Technical Program

ORAL SESSIONS

Wednesday, 30 April

	Room 1	*Room 2*	*Room 3*	*Room 4*	*Room 7*
8:30–9:45 AM	Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships Among Seismic Rupture, Transient Slip, and Steady Creep	Geometric Complexities Along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution	Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales	Site Response: From Site-Specific Analyses to Predictive Models Around the Globe	Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks
10:45 AM–noon					Development of Next Generation Field Methods for Portable Broadband Seismic Arrays
2:15–5:30 PM	Explosive Source Characterization	Deciphering the Earthquake and Tsunami History of Subduction Zones	Fault Structure, Heterogeneity, and Implications for Rupture Dynamics	Pillars of Simulation: Seismic Velocity and Material Models	Emergence of Continuously Recording Very Large Array Capabilities in Seismology

Thursday, 1 May

	Room 1	*Room 2*	*Room 3*	*Room 4*	*Room 7*
8:30–noon	Induced Seismicity	Large and Damaging Earthquakes of 2013/2014	Recent Advances in Ground Motions Simulation Methods and Their Validation	Alaska Update of the USGS National Seismic Hazard Maps	Monitoring Dynamic Changes at Active Volcanoes and Fault Zones
1:30–2:45 PM		Great Earthquakes and Slip to the Trench (*Seismological Society of Japan/ Seismological Society of America Joint Session*)		Seismic Imaging as USArray Moves to Alaska (*IRIS/Seismological Society of America Joint Session*)	Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications
3:45–5:00 PM			Merging Paths: Earthquake Simulations and Engineering Applications		
5:15 PM	Joyner Lecture—Hilton				

Friday, 2 May

	Room 1	*Room 2*	*Room 3*	*Room 4*	*Room 7*
8:30–9:45 AM	From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering	Advances in Understanding Earthquake Hazard in Central and Eastern North America	Seismic Location and Processing Techniques	A Decade of Great Subduction Earthquakes—What Have We Learned From Their Ground-Motions?	Tracking Fluid Movement in Volcanic Systems
10:45 AM–noon			Recent Advances and Findings in Earthquake Geology and Paleoseismology	75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding	
1:30–2:45 PM		New Directions in PSHA: Ins, Outs, and Uncertainty		Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario—Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation	Citizen Seismology: Citizens Helping Science Helping Citizens
3:45–5:00 PM					Earthquake Physics and Interaction

POSTER SESSIONS

	Cook/Arteaga Room
Wednesday	• Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales • Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks • Deciphering the Earthquake and Tsunami History of Subduction Zones • Development of Next Generation Field Methods for Portable Broadband Seismic Arrays • Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships Among Seismic Rupture, Transient Slip, and Steady Creep • Effects of Topography and Surface Loads on Earthquakes and Faulting • Emergence of Continuously Recording Very Large Array Capabilities in Seismology • Explosive Source Characterization • Fault Structure, Heterogeneity, and Implications for Rupture Dynamics • Geometric Complexities Along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution • Pillars of Simulation: Seismic Velocity and Material Models • Site Response: From Site-Specific Analyses to Predictive Models Around the Globe

Thursday

- Alaska Update of the USGS National Seismic Hazard Maps
- Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications
- Great Earthquakes and Slip to the Trench (*Seismological Society of Japan/Seismological Society of America Joint Session*)
- Induced Seismicity
- Large and Damaging Earthquakes of 2013/2014
- Merging Paths: Earthquake Simulations and Engineering Applications
- Monitoring Dynamic Changes at Active Volcanoes and Fault Zones
- Network Operations and Data Centers
- New Insights into Ground Failure as an Urban Earthquake Hazard
- Recent Advances in Ground Motions Simulation Methods and Their Validation
- Seismic Imaging as USArray Moves to Alaska (*IRIS/Seismological Society of America Joint Session*)
- Topics in Seismology: Hazards
- Topics in Seismology: Processes
- Topics in Seismology: Regional Seismicity and Tectonics

Friday

- 75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding
- A Decade of Great Subduction Earthquakes—What Have We Learned From Their Ground-Motions?
- Advances in Understanding Earthquake Hazard in Central and Eastern North America
- Citizen Seismology: Citizens Helping Science Helping Citizens
- Earthquake Physics and Interaction
- Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario—Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation
- From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering
- Near-Field Seismoacoustics of Natural and Man Made Explosions
- New Directions in PSHA: Ins, Outs, and Uncertainty
- Recent Advances and Findings in Earthquake Geology and Paleoseismology
- Seismic Location and Processing Techniques
- Tracking Fluid Movement in Volcanic Systems

Program for 2014 SSA Annual Meeting

Presenting author is indicated in **bold**.

Wednesday, 30 April

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships among Seismic Rupture, Transient Slip, and Steady Creep Session Chairs: Harmony V. Colella, Emily C. Roland, and Aaron G. Wech (see page 416)	**Geometric Complexities along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution** Session Chairs: Sean P. Bemis, Jeff Benowitz, and Michele Cooke (see page 420)	**Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales** Session Chairs: Marco Pilz and Nori Nakata (see page 424)	**Site Response: From Site-Specific Analyses to Predictive Models around the Globe** Session Chairs: Eric Thompson and Dominic Assimaki (see page 428)	**Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks** Session Chairs: Bruce Beaudoin and Christopher Bruton (see page 432)
8:30 AM	INVITED: What Do Seismic Imaging Constraints Really Tell Us about the Fault Zone in Which Great Earthquakes and Slow Slip Operate? **Abers, G. A.**, Kim, Y. H., Shillington, D. J., Saffer, D. M., Li, J., and Janiszewski, H. A.	Dynamic Models of the 2010 Sierra El Mayor-Cucapah Earthquake. **Oglesby, D. D.** and Funning, G. J.	Temporal Changes in Near-Surface Shear Wave Velocity. **Steidl, J. H.**	INVITED: Array Measurements of Rayleigh-Wave Amplitudes to Estimate Site Response. **Tsai, V. C.**, Bowden, D. C., and Lin, F. C.	INVITED: Cold, Wet Seismology: Lessons from Instrumenting Temperate Glaciers. **O'Neel, S.**, Larsen, C. F., West, M. E., Bartholomaus, T. C., Parker, T., Amundson, J., and Walter, J.
8:45 AM	A Link between Silica Enrichment and the Recurrence Time of Slow Earthquakes in Subduction Zone Forearcs. **Audet, P.** and Burgmann, R.	Stress Drop Heterogeneity within Complex Tectonic Regions: A Case Study of the San Gorgonio Pass, Southern California. **Goebel, T. H. W.**, Hauksson, E., Shearer, P. M., and Ampuero, J. P.	Monitoring Temporal Changes in a Levee with Ambient Seismic Noise. **Planés, T.**, Parekh, M., Rittgers, J., Behm, M., Mooney, M., and Snieder, R.	STUDENT: The Importance of the Elastic Half Space Assumption in Site Response Analysis. **Cabas, A.**, Rodriguez-Marek, A., and Green, R. A.	INVITED: Maximizing the Scientific Utility of Broadband Data from Polar Regions. **Nettles, M.**

doi: 10.1785/0220140014

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Diverse Mechanisms. . .	**Geometric Complexities. . .**	**Adv in Seismic Imaging. . .**	**Site Response. . .**	**Cold Climate. . .**
9:00 AM	Laboratory Experiments of Seismic Cycles: Effects of Normal Stress and Its Gradient. **Yamaguchi, T.**, Hori, T., Sakaguchi, H., and Ampuero, J. P.	Comparison of Fault Behavior across the Big Bend of the San Andreas Fault, California. **Scharer, K.**, Weldon, R., Streig, A., Yule, D., and Wolff, L.	Shallow 3D Velocity Imaging by a Joint Rayleigh- and Love-Wave Noise Tomography. **Pilz, M.**, Parolai, S., and Bindi, D.	Site Response Mapping with Fewer Proxies. **Thompson, E. M.** and Wald, D. J.	Polar Seismology: Engineered Solutions from the IRIS/PASSCAL Instrument Center. **Parker, T.**, Carpenter, P., and Beaudoin, B.
9:15 AM	INVITED: Scaling Relations and Along-Strike Segmentation of Episodic Slow Slip Events in Subduction Zones. **Liu, Y.**	Rates and Patterns of Vertical Deformation along the Northern San Andreas Fault. **DeLong, S. B.**, Prentice, C. S., and Hilley, G. E.	STUDENT: Developing 3D Shear Wave Models using a Multi-Objective Joing Inversion Scheme. **Thompson, L. E.**, Velasco, A. A., Garcia, V., Zamora, A., and Sosa, U. A.	Validation of Site-Specific Response Models using KIK-Net Ground Motion Recordings. Shi, J. and **Assimaki, D.**	Ongoing Developments in the Plate Boundary Observatory Alaska Network: Testing New Telemetry and Power Options for Improving Station Robustness. **Boyce, E.**, Enders, M., Bierma, R., Feaux, K., and Mattioli, G. S.
9:30 AM	Similarity and Difference of Megathrust and Slow Tsunami Earthquakes: Interpretation from Observations and Simulation. **Yagi, Y.** and Mitsui, Y.	Did Someone Forget to Pay the Earthquake Bill? **Jackson, D. D.**	STUDENT: Joint Modeling of Complementary Data Functionals for Seismic Site Characterization. **Schwed, M.**, Pulliam, J., Sen, M. K., Willemann, R. J., Huerta-Lopez, C., Moschetti, M. P., Schmitz, M., Louie, J. N., Polanco, E., Huerfano Moreno, V., and Pasyanos, M.	Site Effects in Concepcion Basin: Geometry and Amplification from Gravity and Microtremors. **Montalva, G. A.**, Chavez-Garcia, F. J., Tassara, A., and Jara, D.	Tracking Telemetry State of Health with Nagios. **Bruton, C. P.**
9:45–10:45 AM	Break & Posters – Cook & Arteaga				

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships among Seismic Rupture, Transient Slip, and Steady Creep *(continued)*	**Geometric Complexities along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution** *(continued)*	**Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales** *(continued)*	**Site Response: From Site-Specific Analyses to Predictive Models around the Globe** *(continued)*	**Development of Next Generation Field Methods for Portable Broadband Seismic Arrays** Session Chairs: Timothy Parker and David E. Hawthorn (see page 433)
10:45 AM	INVITED: Geodetic Estimates of Slow and Transient Slip in the Alaska Subduction Zone. **Freymueller, J. T.**, Fu, Y., Li, S., and Ohta, Y.	Basement Structure and Earthquake Hazards along the Queen Charlotte-Fairweather Fault System, Southeastern Alaska. **Walton, M. A. L.**, Gulick, S. P. S., Haeussler, P. J., and Roland, E.	INVITED: The Virtual Eruption of Okmok Volcano, Alaska. **Haney, M. M.**	INVITED: PRENOLIN Project: A Benchmark on Numerical Simulation of 1-D Non-Linear Site Effect. 1 – Site Selection for the Validation Phase. **Regnier, J.**, Kawase, H., Bonilla, L. F., Bard, P. Y., Bertrand, E., Hollender, F., Sicilia, D., and Nozu, A.	Normal Modes: Investigating Signal and Noise Phenomena across Instrument Types and Deployment. **Hellweg, M.**, Araki, E., Rademacher, H., Taira, T., Uhrhammer, R. A., and McGowan, M. G.
11:00 AM	Tectonic Tremor Locations throughout the Alaska-Aleutian Subduction Zone from 1999 to 2013. **Brown, J. R.**	Implications of Recent Large Earthquakes on the Queen Charlotte Fault. **Lay, T.**	Nonlinear Elasticity and Slow Dynamics Observed at the Factor Building (UCLA-California) by Processing Continuous Recordings. **Gueguen, P.**, Roux, P., and Johnson, P. A.	Analysis of Local Earthquake Data from Delaney Park Downhole Seismic Array, Anchorage, Alaska. **Dutta, U.** and Thornley, J. D.	An Analysis of the Tradeoffs between Seismometer Performance and Convenience. **Spriggs, N.** and Greig, D. W.
11:15 AM	Examining Large and Small Earthquakes in the Costa Rica Subduction Zone to Probe Temporal and Spatial Megathrust Heterogeneity. **Bilek, S. L.**, Rotman, H., and Phillips, W. S.	Rupture Behavior on Two Parallel Strike – Slip Faults: A Case from the Central Longriba Fault Zone, Eastern Tibet. **Ren, J. J.**, Xu, X. W., Yeats, R. S., and Zhang, S. M.	Seismological Monitoring of a Tall RC Building in Nice, France. **Bertrand, E.**, Deschamps, A., Santisi d'Avila, M. P., Gueguen, P., Tahmi, N., and Fernandez-Lorenzo, G.	Lessons Learned from Conducting Seismic Site Response Analyses That Require Explicit Consideration of the Site Attenuation Parameter. **Kottke, A. R.**, Hashemi, A., and Elkhoraibi, T.	What Should I Do with the S13? – Or Better: How to Teach New Tricks to an Old Dog. **Braun, T.**, Romeo, G., and Spinelli, G.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Diverse Mechanisms. . .	**Geometric Complexities. . .**	**Adv in Seismic Imaging. . .**	**Site Response. . .**	**Dev of Field Methods. . .**
11:30 AM	Observations of SSE, Tremor, and Damaging Earthquakes on the Southern Hikurangi Margin, New Zealand. **Fry, B. N.** and Wallace, L.	Modeling Observed Aftershock Sequences with an Earthquake Simulator. **Kroll, K. A.**, Richards-Dinger, K. B., and Dieterich, J. H.	INVITED: Noise-based Crustal Seismic Velocity Changes Associated with the 2011 Tohoku-oki Earthquake. Brenguier, F., **Campillo, M.**, Briand, X., Takeda, T., Aoki, Y., Shapiro, N., and Emoto, K.	Seismic Site Amplification in the Port Hills during the Canterbury Earthquake Sequence: Case Study of Critical Slopes **Kaiser, A. E.**, Holden, C., and Massey, C.	STUDENT: A Microseism Catalog Based on Broadband Data from the US Transportable Array. **Sufri, O.**, Koper, K. D., and Burlacu, R.
11:45 AM	The Downdip Location of ETS and Dehydration Fluids Channelled to Forearc Mantle Corner. **Hyndman, R. D.**, McCrory, P. A., and Wech, A. G.	Strike-Slip Fault Segment Propagation and Linkage via Work Minimization. **Cooke, M. L.**, Madden, E. H., and McBeck, J.	Depth Constraint of Velocity Changes caused by the 2011 Tohoku-Oki Earthquake. **Nakata, N.** and Lawrence, J. F.	Calibration and Evaluation of Response Spectra in the Downtown Area of Anchorage, Alaska. **Thornley, J. D.**, Dutta, U., and Yang, Z.	A Ground-Truth Mine Monitoring System Authors: **Taylor, S. R.,** Jarpe, S. P., Harben, P. E., Harris, D. B.
Noon–2:00 PM	Annual Luncheon – La Perouse				
Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Explosive Source Characterization Session Chairs: Catherine Snelson, Christopher Bradley, Sean Ford, and Kyle Jones (see page 417)	**Deciphering the Earthquake and Tsunami History of Subduction Zones** Session Chairs: Marco Cisternas, Lisa Ely, Ed Garrett, Daniel Melnick, Alan Nelson, and Robert Wesson (see page 422)	**Fault Structure, Heterogeneity, and Implications for Rupture Dynamics** Session Chairs: Thomas H. W. Goebel, Thibault Candela, and Heather Savage (see page 426)	**Pillars of Simulation: Seismic Velocity and Material Models** Session Chairs: Ricardo Taborda, Po Chen, and En-Jui Lee (see page 430)	**Emergence of Continuously Recording Very Large Array Capabilities in Seismology** Session Chairs: Rick Aster and James Gridley (see page 434)
2:15 PM	Hydrodynamic Modeling of the Near-Source Environment at a Jointed Site. Bradley, C. R., **Steedman, D. S.**, Rougier, E., and Knight, E. E.	The 1730 and 1751 Chilean Earthquakes: Two Major Contributors to the Seismically Prolific 18th Century along the Pacific Coast of the Americas. **Cisternas, M.**, Ely, L., Wesson, R., Pilarckzic, J., Gorigoitia, N., Dura, T., Melnick, D., and Carvajal, M.	BIEM Simulation for Anti-Plane Dynamic Rupture Propagation across a Bimaterial Interface. **Hirano, S.** and Yamashita, T.	Seismic Wavefield Simulations of Earthquakes within a Complex Crustal Model for Alaska. **Tape, C.**	Back-Projection Imaging of Aftershocks Recorded by the Dense AIDA Array after the 2011 Virginia Earthquake. **Hole, J. A.**, Wang, K., Davenport, K. K., Chapman, M. C., Beskardes, G. D., Quiros, D. A., Brown, L. D., and Mooney, W. D.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Explosive Source Char. . .	**Deciphering the Earthquake. . .**	**Fault Structure. . .**	**Pillars of Simulation. . .**	**Emergence of Continuously. . .**
2:30 PM	A New Fracture Material Model for Simulating Damage and Moment Tensor Descriptions of Simulated Explosion Sources for Source Physics Experiments (SPE). **Rougier, E.**, Yang, X., Knight, E. E., and Patton, H. J.	A Comparison of Tsunami Deposits from the 1960 Great Chilean Earthquake in Two Coastal Lakes on Chiloé, Chile. **Kempf, P.**, Moernaut, J., Vandoorne, W., Van Daele, M., Pino, M., Urrutia, R., and De Batist, M.	STUDENT: 3D Dynamic Rupture Simulation across a Complex Fault System: The Mw7.0, 2010, Haiti Earthquake. **Douilly, R.**, Aochi, H., Calais, E., and Freed, A. M.	Full-3D Waveform Tomography for Crustal Structure in Southern California using Earthquake Recordings and Ambient-Noise Green's Functions Based on the Adjoint and the Scattering-Integral Methods. **Lee, E.**, Chen, P., Jordan, T. H., Maechling, P. J., Denolle, M., and Beroza, G. C.	Aftershock Imaging with Dense Arrays (AIDA). **Brown, L.**, Hole, J., Quiros, D., Davenport, K., Wang, K., Cabolova, A., and Mooney, W.
2:45 PM	Three Dimensional Simulation of Ground Motions Generated by Underground Explosions in Jointed Rock under Conditions of Uncertainty. **Ezzedine, S. M.**, Vorobiev, O. Y., Glenn, L. A., and Antoun, T. H.	Linking Subduction-Earthquake Supercycles with Mountain Building in the Region of the Giant 1960 Chile Earthquake. **Melnick, D.**, Cisternas, M., Wesson, R. L., Moreno, M., Nelson, A., Jara-Munoz, J., Dura, T., and Engelhart, S.	Dynamic Rupture Models of Earthquakes on the Bartlett Springs Fault, Northern California. **Lozos, J. C.**, Harris, R. A., Murray, J. R., and Abrahamson, N. A.	Validation of Physics-Based Ground Motion Earthquake Simulations Using a Velocity Model Improved by Tomographic Inversion Results. **Taborda, R.**, Lee, E. J., Gill, D., Chen, P., Maechling, P. J., and Jordan, T. H.	Optimal Design of Large-Scale Seismic Array for Earthquake Source Imaging Constrained by Waveform Coherency of USArray. **Meng, L.** and Ampuero, J. P.
3:00 PM	Implications for Chemical/Nuclear Equivalence from Observations and Hydrodynamic Calculations. **Patton, H. J.** and Rougier, E.	Two Centuries of Emergence in Northern Chiloé before Sudden Submergence Associated with the Giant 1960 Chile Earthquake. **Wesson, R. L.**, Cisternas, M., Melnick, D., Moreno, M., and Ely, L.	Stick-slip Instability in Granite Initiated as Acoustic Emission Event. **McLaskey, G. C.** and Lockner, D. A.	Stochastic Descriptions of Fine-Scale Basin Velocity Structure from Well Logs and the SCEC Community Velocity Model (CVMH). **Plesch, A.**, Shaw, J. H., Song, X., and Jordan, T. H.	STUDENT: The New Wave Gradiometry Technique Applied to USArray. **Liu, Y.** and Holt, W. E.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Explosive Source. . .	**Deciphering the Earthquake. . .**	**Fault Structure. . .**	**Pillars of Simulation. . .**	**Emergence of Continuously. . .**
3:15 PM	Modeling r_{el} as the Nonlinear Inelastic-Elastic Transition near Explosion Source. **Morozov, I. B.** and Stroujkova, A.	Understanding Mega-Earthquake Related Tsunami on Subduction Zones without Large Historical Events. **Williams, C. R.**, Mohammed, F., and Lee, R.	Seismic Moment Tensors and b-values of Acoustic Emissions during Stick Slip Sliding Tests. **Kwiatek, G.**, Goebel, T., and Dresen, G.	STUDENT: Rupture Dynamics and Ground Motions from Earthquakes in Heterogeneous Media. **Bydlon, S. A.**, Kozdon, J. E., and Dunham, E. M.	STUDENT: A Comparison between Seismic Wave Gradiometry and fK Analysis in the Estimation of the Slowness Vector. **Hughes, A.** and Poppeliers, C.
3:30–4:30 PM	Break & Posters – Cook & Arteaga				
4:30 PM	Relocation, Discrimination, Magnitude Calculation and Yield Estimation of the 12 February 2013 North Korean Nuclear Test. **Zhao, L. F.**, Xie, X. B., Fan, N., Wang, W. M., and Yao, Z. X.	Great Earthquakes and Tsunamis during the Last 1000 years in the Kodiak Segment of the Alaska-Aleutian Megathrust. **Shennan, I.**, Barlow, N. L. M., Carver, G., Davies, F. P., Garrett, E., and Hocking, E. P.	Fault-Zone Maturity Defines Maximum Earthquake Magnitude. **Bohnhoff, M.**, Bulut, F., Stierle, E., and Ben-Zion, Y.	Couple-Stresses in Elastodynamics and Quantitative Seismology. **Dargush, G. F.** and Hadjesfandiari, A. R.	Long Beach 3D Seismic Survey: Data Mining Continuous Passive Seismic Data. **Hollis, D. D.**
4:45 PM	Seismic Analysis of the North Korean Nuclear Explosion on February 12, 2013. **Vavrycuk, V.** and Kim, S. G.	Same Asperity, Different Rupture Pattern: Variations in Holocene Splay Fault Motion from Seward to Middleton Island, Alaska. **Liberty, L. M.**, Haeussler, P. J., and Finn, S. P.	The Role of Iquique Area in a Future Large Earthquake – A Multi-disciplinary Approach. **Sobiesiak, M. M.**, Goetze, H. J., Meneses, G., Schaller, T., Eggert, S., Victor, P., Boudin, F., Campos, J., Vilotte, J.P., Métois, M., Madariaga, R., Olcay, M., and Tassara, C.	Physical Characterization of Seismic Attenuation in Earth Models. **Morozov, I. B.**	STUDENT: Body and Surface-Wave Ambient-Noise Seismic Interferometry across the Salton Sea Geothermal Field, California. **Sabey, L. E.**, Hole, J. A., Han, L., Stock, J. M., and Fuis, G. S.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Explosive Source. . .	**Deciphering the Earthquake. . .**	**Fault Structure. . .**	**Pillars of Simulation. . .**	**Emergence of Continuously. . .**
5:00 PM	STUDENT: Ms Unified: A New Magnitude for Rayleigh and Love Waves with Application in the Korean Peninsula and Yellow Sea Region. **Napoli, V.**, Bonner, J., and Russell, D.	Field Studies of the 2012 Mw 7.7 Haida Gwaii Tsunamigenic Thrust Earthquake: Implications for Paleoseismic and Paleotsunami Studies of Subduction Zones. **Leonard, L. J.**, Bednarski, J. M., Rogers, G. C., Nykolaishen, L., Wang, K., Haeussler, P. J., and Witter, R. C.	Fully Automated Real-time 3D Earthquake Locations in the San Jacinto Fault Zone Using High Resolution 3D Velocity Models. **Allam, A. A.**, Vernon, F. L., and Ben-Zion, Y.	STUDENT: Anelastic Attenuation and Elastic Scattering Models of the Los Angeles Region for Use in Earthquake Simulations. **Song, X.** and Jordan,	STUDENT: Impact of Scattering on the Design of a Network of Arrays for Earthquake Rupture Imaging. **Bowden, D. C.**, Ampuero, J. P., and Meng, L.
5:15 PM	Identifying and Characterizing Blasts from Recordings at USArray Stations. **Astiz, L.**, Vernon, F. L., Martynov, M. V., Tytell, J., Cox, T. A., White, M. C., Reyes, J., and Eakins, J.	The 1861–2005 Simeulue–Nias Slip Patch of the Sunda Subduction Zone: Characteristic Slip on an Otherwise Non-characteristic Megathrust. **Meltzner, A. J.**, Sieh, K., Chiang, H. W., Shen, C. C., Wu, C. C., Suwargadi, B. W., Natawidjaja, D. H., Philibosian, B., and Briggs, R. W.	Imaging Tremor Dynamics at the San Andreas Fault near Parkfield with a Mini Seismic Array. **Ghosh, A.**	Regional Phase Attenuation in the Iranian Plateau and Surrounding Regions. **Sandvol, E.**, Kaviani, A., Ku, W., and Gok, R.	"No-Cost" Acquisition of 3D Reflection Imagery of the Continental Basement. **Brown, L. D.**
5:30 PM	Improving Yield Estimation for Near-Surface Explosions Using Seismic And Overpressure Data. **Rodgers, A. J.**, Bonner, J. L., Ford, S. R., Templeton, D. C., Ramirez, A. L., and Dodge, D.	Stratigraphic Evidence of the 2004 Sumatra-Andaman Subduction Zone Seismoturbidite. **Patton, J. R.**, Goldfinger, C., Djadjadihardja, Y., and Udrekh, U.	Slip Characteristics of the Deep Portion of the San Andreas Fault Inferred from Low-Frequency Earthquakes. **Wu, C.**, Guyer, R. A., Trugman, D. T., Shelly, D. R., and Johnson, P. A.	Finite-frequency Sensitivity of Seismic Waves to Fault Zone Structures. **Allam, A. A.**, Tape, C., and Ben-Zion, Y.	Discussion

Wednesday, 30 April – Morning Poster Sessions

Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales
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1. Lithospheric Earth Structure of Texas-Gulf of Mexico Margin from Surface Wave Dispersion and Migrated Ps Receiver Functions. **Agrawal, M.**, Pulliam, J., and Sen, M. K.
2. P Wave Transfer Functions for the Northern Mississippi Embayment: A Different Approach. **Mostafanejad, A.** and Langston, C. A.
3. 3D Shear Wave Model Development of the Texas Region Using an Optimization Scheme. Thompson, L. E., Velasco, A. A., and **Garcia, V. H.**
4. Shear Wave Velocity Structure beneath Haida Gwaii, Canada, in the Vicinity of the 2012 Mw 7.7 Earthquake. **Cassidy, J. F.**, Gosselin, J., and Dosso, S. E.
5. 3D Seismic Reflection Imaging Using Aftershocks of the 2011 Central Virginia Earthquake as Illumination Sources. **Quiros, D.**, Brown, L. D., Davenport, K., and Hole, J.
6. Group Velocity Tomography for Eastern Mexico and Isthmus of Tehuantepec. Córdoba, F., **Iglesias, A.**, Singh, S. K., Spica, Z., and Legrand, D.
7. Ambient Noise Tomography of the Katmai Volcanic Complex, Alaska. **Lemon, S.**, Thurber, C. H., Haney, M. M., Syracuse, E., Zhang, H., Zeng, X., and Prejean, S. G.
8. Shear-Wave Quality Factor Qs Profiling Using Seismic Noise Data from Microarrays. **Parolai, S.**, Boxberger, T., Pilz, M., and Bindi, D.
9. Extracting Site Characteristics at Delaney Park Geotechnical Array in Anchorage, Alaska Using Seismic Interferometry. **Kalkan, E.**, Ulusoy, H. S., Wang, F., and Fletcher, J. P.
10. Site Characterization for Marine Earthquake Engineering via Modeling of Ocean-Bottom-Seismometer Observations of Rayleigh Waves and Microtremors. **Li, Z. W.**, Hao, T. Y., Ni, S. D., You, Q. Y., Liu, L. H., Bao, F., and Xu, Y.
11. A Wave Gradiometry Application in Engineering Seismology: Field Measurement of Nonlinear Soil Behavior in the Near Surface. **Dangkua, D. T.**, Langston, C. A., and Cramer, C. H.
12. Sediment Shear Velocity and Thickness from Seafloor Compliance using Microseisms Noises. **Ruan, Y.**, Forsyth, D. W., and Bell
13. Instantaneous Monitoring of Soil and Structure Dynamics using Autocorrelation Functions Computed with the Stockwell Transform. Bonilla, L. F. and **Gueguen, P.**
14. Monitoring a Building Using Deconvolution Interferometry from Earthquake and Ambient-Noise Data. **Nakata, N.** and Snieder, R.
15. Dynamic Response Characterization of a Highway Bridge Using Ambient Vibrations. **Mercerat, E. D.**, Regnier, J., Bertrand, E., and Deni, D.
16. Application of Instantaneous Phase Methods for Improved Noise-Correlation-Derived Dispersion Measurements from a Local Seismic Array. **Moschetti, M. P.**, Noriega, R., Stephenson, W., and Meremonte, M.
17. Reliable Estimation of Shear-Wave Velocity Profile by Inverting Phase Velocity Dispersion Curve and Waveform Comparison. **Hosseini, M.**, Pezeshk, S., and Pujol, J.
18. Monitoring Pre-Earthquake Activity by Analysis of Ambient Seismic Noise – Encouraging Results. **Gupta, I. N.** and Schaff, D. P.

Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks
(see page 440)

19. The Seismic Noise Environment of the Antarctic and the Influence of Instrumentation Techniques. **Anthony, R. E.**, Aster, R. C., Wiens, D. A., Nyblade, A., Anandakrishnan, S., Winberry, J. P., Huerta, A. D., and Wilson, T. J.
20. Seismic Noise Analyses and Event Quality Assessment for EarthScope Transportable Array Stations in Alaska. **Frassetto, A. M. F.**, Busby, R., Hafner, K., Woodward, R., Astiz, L., Sharer, G., and Sauter, A.
21. Development of New Seismological Instrumentation for Ice Covered Environments. **Bernsen, S.**, Winberry, P., Aster, R., Woodward, R., Carpenter, P., Beaudoin, B., and Gridley, J.
22. Running Real-Time, Year-Round Seismic Stations across the Greenland Ice Sheet. **Childs, D.** and Reusch, M. M.
23. The Yukon-Northwest Seismograph Network: Preliminary Results of Direct Burial Posthole Installation for Real-Time Monitoring. **Audet, P.**
24. The Alaska Volcano Observatory's Experience in Operating Multi-Parametric Real Time Monitoring Systems in Remote and Challenging Environments. **Read, C. W.**, Power, J. A., Paskievitch, J. F., and Ketner, D. M.
25. Development of Seismic Field System for Multi-Year Field Deployment at Poker Flat Research Range, Alaska. **Hart, D.** and Abbott, R. E.
26. Minimizing Snow Losses for Photovoltaic Systems in High-Latitude Maritime Environments. **Dalton, S. M.**

Deciphering the Earthquake and Tsunami History of Subduction Zones
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27. Tsunami Recurrence in the Eastern Aleutian Arc: A Record of 6-14 High Tsunamis in 3400 Years on Chirikof Island, Alaska. **Nelson, A. R.**, Briggs, R. W., Dura, T.,

Engelhart, S. E., Gelfenbaum, G., Bradley, L. A., Forman, S., and Vane, C. H.

28. Evidence for High Tsunamis in the Fox Islands Implies Repeated Aleutian Megathrust Earthquakes in the Unalaska Seismic Gap. **Witter, R. C.**, Briggs, R. W., Koehler, R. D., Gelfenbaum, G., Engelhart, S., Nelson, A. R., Carver, G. A., Bender, A. M., and Hemphil-Haley, E.
29. Using Tsunami Deposits to Inform Modeling of Potential Tsunamigenic Earthquake Rupture Zones near Unalaska Island, Aleutian Islands. **La Selle, S. P. M.**, Gelfenbaum, G., Witter, R. C., Koehler, R. D., Briggs, R. W., Carver, G. A., and Engelhart, S. E.
30. Unrevealing the History of Earthquakes and Tsunamis of the Mexican Subduction Zone. **RamirezHerrera, M. T.**, CastilloAja, R., Cruz, S., Lagos, M., Rangel, V., and Nava, H.

Development of Next Generation Field Methods for Portable Broadband Seismic Arrays
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31. Crustal Structure of the St. Lawrence Corridor from Montreal to the Charlevoix Seismic Zone from a Temporary Broadband Array. **Bent, A. L.** and Kao, H.
32. Performance Modeling of the Transportable Array in Alaska: Estimated Magnitude of Completeness and Location Accuracy. **Ackerley, N. J.**
33. Northern Embayment Lithospheric Experiment (NELE): Summary, Status and Noise Analysis. NELE Team (**Langston, C.**)
34. Analysis of Micro-Earthquakes in the Sierra Madre-Cucamonga Fault Zone Transition as Recorded by a Temporary Seismic Deployment. **Pazos, C. S.**, Levario, J. J., Nget, D., and Polet, J.
35. What Have We Learned from Data from Purpose-Built, Direct-Bury Sensors at Poker Flat, Alaska? **Slad, G. W.**, Anderson, K. E., Reusch, M. M., Hutton, W., Miller, P., Pfiefer, C., Barstow, N., Parker, T., Beaudoin, B., and Gridley, J.
36. A Discussion of Seismic Velocity Models, Attenuation and Stochastic Properties as Indicators of EGS Favorability in Dixie Valley NV. **Tibuleac, I. M.** and Iovenitti, J.

Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships among Seismic Rupture, Transient Slip, and Steady Creep
(see page 444)

37. Temporal Variation of A Large Slow Slip Event at the Southcentral Alaska Subduction Zone during 2009–2013. **Fu, Y.**, Freymueller, J. T., Argus, D. F., and Owen, S. E.
38. Network Matched Filtering as a Tool for Characterizing Seismic Sequences in Alaska. **Holtkamp, S. G.**
39. Potential Causes for Along-Strike Variability of Slow Slip Events in South-Central Alaska. **Watkins, W. D.**, Colella, H. V., Brudzinski, M. R., Dieterich, J. H., and Richards-Dinger, K. B.
40. A Provably Stable Finite-Difference Method for Earthquake Cycle Simulations within Subduction Zones. **Erickson, B. A.** and Day, S. M.
41. SSE-Related Seismicity on the Northern Hikurangi Subduction Margin, New Zealand. **Bannister, S.**, Obara, K., Wallace, L., Bourguignon, S., Fry, B., D'Anastasio, E., and Eberhart-Phillips, D.
42. Earthquake Triggering along the Hikurangi Margin: Implications for Fault Strength and Stability. **van der Elst, N. J.** and Savage, H. M.
43. High Resolution Detection and Location of Low Frequency Earthquakes Using Cross-station and Cross-detection Correlation. **Savard, G.** and Bostock, M. G.
44. PBO Strainmeter Measurements of Cascadia Episodic Tremor and Slip Events. **Hodgkinson, K. M.**, Phillips, D., Mencin, D., Henderson, B., Gottlieb, M., Gallaher, W., Johnson, W., Pyatt, C., Van Boskirk, Fox, Puskas, Mattioli, Meertens
45. Tremor and Seismicity in the Northern Costa Rica Seismogenic Zone Leading up to the September 5, 2012 Earthquake. **Taylor, S.**, Chaves, E. J., and Schwartz, S. Y.
46. Comparison of Velocity and Attenuation Patterns along the Frictionally Heterogeneous Nicaragua-Costa Rica Seismogenic Zone. **Moore-Driskell, M. M.**, Bisrat, S. T., and DeShon, H. R.
47. Examining Apparent Stress in Microseismicity along the Costa Rican and Southern Nicaragua Segments of the Middle America Trench. **Rotman, H. M. M.**, Bilek, S. L., and Phillips, W. S.
48. Spatio-Temporal Variations of Afterslip and Aftershocks Reveal the Role of Fluids at the Megathrust Ruptured by the Mw8.8 2010 Maule (Central Chile) Great Earthquake. **Tassara, A.**, Soto, H., Bedford, J., Moreno, M., and Baez, J. C.
49. Temporal Variations of Intraplate Earthuake Activity Following the 2011 Tohoku-Oki Earthquake. **Delbridge, B.**, Matsuzawa, T., Kita, S., Buffett, B., and Roland, B.
50. Interaction of Trench-Parallel Fault Systems and the Subduction Zone Earthquake Cycle Investigated with the IPOC Creepmeter Array in N-Chile. **Victor, P.**, Sobiesiak, M., Schurr, B., Gonzalez, G. L., and Oncken, O.

Effects of Topography and Surface Loads on Earthquakes and Faulting
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51. Crustal Deformation from Surface Loading in the Great Salt Lake Region. **Amosu, A. M.**, and Smalley, R.
52. Heterogeneous Initial Stress States for Dynamic Rupture Propagation in the 2008 Mw 7.9 Wenchuan Earthquake. **Duan, B.**
53. The Influence of Stresses from Topography on the 2008 Wenchuan, China Rupture: Implications for Tectonic Stresses and Rupture Processes. **Styron, R. H.** and Hetland, E. A.
54. Coseismic Slip in the 2013 Lushan, China Earthquake and Topographic Fault Loading. **Hetland, E. A.**, Styron, R. H., Zhang, G., and Medina Luna, L.
55. Coulomb Stress, Surface Displacement and Seismic Rate Changes Associated with Ice Mass Fluctuations on Seasonal, Annual, and Decadal Time Scales in South Central Alaska. **Sauber, J.** and Ruppert, N.
56. The Role of Frictional Softening and Erosion on Thrusting Sequences in Accretionary Prisms Based on Sequential Limit Analysis. **Mary, B. C. L.**, Maillot, B., and Leroy, Y. M.

Emergence of Continuously Recording Very Large Array Capabilities in Seismology
(see page 448)

57. Retrieval of Core Phases from Ambient Noise Cross-correlation Using a Dense Large-aperture Broadband Array in Southwest China. **Wang, W. T.**, Tsai, C. V., and Wang, B. S.
58. An Earthquake Detection Algorithm with Pseudo-Probabilities of Multiple Indicators. **Ross, Z. E.** and Ben-Zion, Y.
59. Recovering Seismic Green's Functions Using Icequake Coda Interferometry at Erebus Volcano, Antarctica. **McMahon, N. D.**, Chaput, J. A., Knox, H. A., Aster, R. C., and Kyle, P. R.
60. Determining the Geometry and Kinematics of an Earthquake Fault Using Seismic Gradiometry. **Overman, K. E. O.** and Poppeliers, C. J. P.
61. Rupture Speeds of Recent Large Earthquakes. **Wang, D.**, Mori, J., and Koketsu, K.
62. Earthquake Locations Using a Wave Gradiometer in Southern Illinois. **Meredith, J. A.** and Langston, C. A.

Explosive Source Characterization
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63. Understanding Shear Motion from Underground Explosions in Granite. **Vorobiev, O. Y.**, Stroujkova, A., Ezzedine, S. M. E., Herbold, E. B., Glenn, L., and Antoun, T.
64. Coupled Non-linear and Linear Acoustic Wave Propagation Codes for Explosion Monitoring. **Preston, L.** and Jones, K. R.
65. Comparing Modeled and Observed Infrasound Signals from the Source Physics Experiment Tests 2 and 3. **Jones, K. R.**, Whitaker, R. W., and Arrowsmith, S. J.
66. USArray Acoustic Capabilities Confirm Significant Meteor Sighting. **Edwards, W. N.**, de Groot-Hedlin, C. D., and Hedlin, M. A. H.
67. Fiber Optic Acoustic Sensing (FOAS) Far-Field Observations of SPE 3. **Mellors, R. J.**, Pitarka, A., Kuhn, M., Stinson, B., Ford, S. R., Snelson, C., and Drachenberg, D.
68. Waveform Analysis of Scholte Waves Observed in San Diego Trough using a Seafloor Source and OBS. **Dorman, L. M.**
69. Seismic-Wave Gradiometry Applied to a Small-Scale Exploration Dataset. **Kendall, L.** and Langston, C. A.
70. Yield and Depth of the SPE Chemical Explosions by Modeling of Local Waveforms Using a Source Consisting of Pure Explosion and Spall Sources. **Saikia, C. K.** and Woods, M.
71. Resolving Focal Depth with a Near Field Single Station in Sparse Seismic Network. **Ni, S.** and He, X.
72. Isotropic Source Rerms of San Jacinto Fault Zone Earthquakes based on Waveform Inversions with a Generalized CAP Method. **Ross, Z. E.**, Ben-Zion, Y., and Zhu, L.
73. Full Moment Tensors for Small (Mw $<$ 3) Events at Uturuncu Volcano, Bolivia. **Alvizuri, C.** and Tape, C.
74. Time-Dependent Moment Tensors of the First Three Source Physics Experiments Explosions. **Yang, X.**, Patton, H. J., Rowe, C. A., and Larmat, C.
75. A Spall Model Comparison with Insights from the Source Physics Experiment. **Ford, S. R.**, Mellors, R. J., and Vorobiev, O. Y.
76. Local Distance Application of P/S Methods of Discriminating Explosions from Earthquakes – How Low Can We Go? **Walter, W. R.**, Pyle, M., Ford, S. R., and Pasyanos, M. E.
77. Source Physics Experiment Site Characterization: Earthquake Relocation and Southern Nevada Attenuation Structure. **Pyle, M. L.**, Walter, W. R., Pasyanos, M. E., Myers, S. C., Smith, K. D., and Hauk, T. F.
78. High Resolution Imagery of the Source Physics Experiment Site Using Seismic Interferometry. **Matzel, E.**, Pitarka, A., and Mellors, R.
79. 3D Modeling of Rg Wave Propagation on Geophone Lines Recording the Source Physics Experiment. **Larmat, C. S.**, Rowe, C. A., Coblentz, D. D., and Patton, H. J.
80. Structural Heterogeneity at the SPE Site Revealed Through Combined P-Wave Travel Times and Sub-Band

Rg Phase Velocities. **Rowe, C. A.**, Patton, H. J., Yang, X., Larmat, C., and Coblentz, D.

81. A New Database of Digitized Regional Seismic Waveforms from Underground Nuclear Explosions in Eurasia. Kim, W. Y., Mikhailova, N. N., **Richards, P. G.**, and Sokolova, I. N.
82. High Frequency Network Discrimination Using MLE Source spectra From Global Amplitude Tomography. **Phillips, W. S.**, Fisk, M. D., Stead, R. J., Begnaud, M. L., Yang, X., and Ballard, S.

Fault Structure, Heterogeneity, and Implications for Rupture Dynamics
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83. Modeling Fault Rupture Process by Lagrange Discontinuous Deformation Analysis Method. **Cai, Y.**
84. Re-visiting Linear Source Inversion with the Full Complexity of Earthquake Rupture, Including Both Slip Re-activation and Supershear Rupture. **Song, S. G.** and Dalguer, L. A.
85. Fault Slip Heterogeneity of the 2008 Mw 7.9 Wenchuan, China, Earthquake and Implications for Regional Tectonic Stresses. **Medina Luna, L.** and Hetland, E. A.
86. High-Resolution Geophysical Imaging across the Olympia Structure, Southern Puget Lowland, WA: Defining a Fault System. **Odum, J. K.**, Stephenson, W. J., Pratt, T. L., and Blakely, R. J.
87. Rate-and-State Coulomb Stress Evolution: a Pseudo-Prospective Southern California Earthquake Forecast. **Strader, A. E. S.** and Jackson, D. D. J.
88. High-Resolution Aftershock Distribution of 2010 Mw6.9 Yushu, China Earthquake and Its Implication. **Wang, B.**, Yang, H., Peng, Z., Yang, J., Han, L., Yang, W., Yuan, S., and Meng, X.
89. Velocity Contrast along Ganzi-Yushu Fault from Analysis of Fault Zone Head Waves Associated with Aftershocks of 2010 Mw6.9 Yushu, Qinghai Earthquake. **Yang, W.**, Peng, Z. G., Wang, B. S., Li, Z. F., Meng, X. F., Yuan, S. Y., and Qiao, S.

Geometric Complexities along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution
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90. Determination of Lithosphere Rheology from Interseismic Deformation and Implications for Fault Stress Accumulation. **Hines, T. T.** and Hetland, E. A.
91. Unraveling Enigmas in the GPS Velocity Field in the Big Bend Region of the Southern San Andreas Fault System. **Thatcher, W.**
92. Fault Interaction in the San Gorgonio Pass Region of the San Andreas Fault, Southern California. **Kendrick, K. J.** and Matti, J. C.
93. Paleoseismology of the Northern San Jacinto Fault Zone and Implications for Rupture across Steps in the San Andreas Fault System, Southern California. **Onderdonk, N. W.**, McGill, S. F., and Rockwell, T. K.
94. Rupture and Ground Motion Models on the Claremont-Casa Loma Stepover of the San Jacinto Fault, Incorporating Realistically Complex Initial Conditions. **Lozos, J. C.**, Olsen, K. B., Oglesby, D. D., and Brune, J. N.
95. Geometric Complexities of Hosgri Fault Zone Offshore Point Sal, Central Coastal California. **Hogan, P. J.**, Nishenko, S. P., Greene, H. G., and Bergkamp, B. J.
96. Newly Acquired 2D and 3D Multichannel Seismic Datasets from the Inner California Borderlands Yield New Constraints on the Timing and Style of Recent Deformation. **Bormann, J. M.**, Holmes, J. J., Driscoll, N. W., Kent, G. M., Harding, A. J., Maloney, J. M., and Ucarkus, G.
97. Aftershocks Following the January 5th 2013 Queen Charlotte-Fairweather Fault Earthquake near Craig, Alaska from Offshore Seismic Observations. **Roland, E. C.**, Ruppert, N. A., Gulick, S., Haeussler, P., and Walton, A. L.
98. Quaternary Crustal Deformation at the Apex of the Mount McKinley Restraining Bend of the Denali Fault, Alaska. **Burkett, C. A.**, Bemis, S. P., Benowitz, J. A., and Walker, L. A.
99. Insight into the Evolution of the Mount McKinley Restraining Bend Through Thermochronology: Long-Term Controls on Slip Distribution. **Benowitz, J. A.**, Bemis, S. P., Burket, C. A., and O'Sullivan, P. B.
100. Analog Modeling of Restraining Bends: A Study of Strike-Slip Fault Evolution. **Hatem, A. E.**, Cooke, M. L., and Madden, E. H.

Pillars of Simulation: Seismic Velocity and Material Models
(see page 457)

101. UCVM: Open Source Software Framework for 3D Seismic Velocity Models. **Gill, D.**, Small, P., Maechling, P., Jordan, T., Plesch, A., Taborda, R., and Callaghan, S.
102. Two-Station Micro-Tremor Measurements to Detect the Depth to Bedrock in Sultan, Washington. **Hayashi, K.**, Cakir, R., Walsh, T. J., and Dragovich, J. D.
103. Detection of Shallow Crustal Discontinuities from High-Frequency Waveforms of Local Microearthquakes. **Hrubcova, P.**, Vavrycuk, V., and Bouskova, A.

104. Detailed Crustal Structure of the North China and Its Implication for Seismic Activity. **Jiang, W. L.**, Zhang, J. F., Wang, X., and Tian, T.
105. Frequency Dependent Lg Attenuation in Northeast China. **Ni, N. R.**, Gallegos, A. C., Trujillo, A. R., Sandvol, E. A., Ni, J., Hearn, T. M., Tang, Y., Grand, S. P., Niu, F.L, Chen, Y. J., Ning, J. Y., Kawakatsu, H., Tanaka, S., and Obayashi, M.
106. High Resolution Regional Travel-Time Tomography in South-Central Tibet: Imaging Tibetan Crust beneath the Hi-CLIMB Array. **Riddle, E.**, Nabelek, J. L., and Braunmiller, J.
107. Sn Attenuation in Northeast China. **Yan, Q.**, Sandvol, E., and Ku, W.
108. Mechanisms of Postseismic Deformation Following the 2010 M = 7.2 El Mayor-Cucapah Earthquake. **Rollins, J. C.**, Barbot, S. D., and Avouac, J. P.
109. Separation of the Earthquake Tomography Inverse Problem to Refine Hypocenter Locations and Tomographic Models: A Case Study from Central Oklahoma. **Toth, C. R.**, Chen, C. C., and Holland, A. A.
110. Detailed Near Surface Velocity Model and Site Response of the Hayward, East San Francisco Bay Area: 2D Velocity Model Based on Active and Passive Surface Wave Methods. **Craig, M. S.** and Hayashi, K.

Site Response: From Site-Specific Analyses to Predictive Models around the Globe
(see page 459)

111. Detailed Near Surface Velocity Model and Site Response of the Hayward, East San Francisco Bay Area: Seismic Observation of a Building Implosion and its Interpretation from Site Response Point of View. **Hayashi, K.** and Craig, M.
112. Effect of Site Models on Standard Deviation of GMPEs and Fundamental Site Frequency as a New Complementary Site Parameter. **Sandikkaya, M. A.**, Bard, P. Y., and Akkar, S.
113. Empirical Assessment of Site Effects in Low Seismicity Areas. **Perron, V.**, Hollender, F., Guyonnet-Benaize, C., Bard, P. Y., and Gélis, C.
114. Rock and Stiff-Soil Site Amplification: Dependency on V_{S30} and kappa ($k_0 >$). **Laurendeau, A.**, Cotton, F., Ktenidou, O. J., Bonilla, L. F., and Hollender, F.
115. Site Response in Western Washington from Specral Ratios. **Keshvardoost, R.** and Wolf, L. W.
116. Site Amplification Using Generalized versus Hazard-Consistent Ground Motion: A Site-Specific Comparative Case-Study in CEUS. **Li, W.**, Quittmeyer, R. C., Kimball, J. K., Blanco, J. E., and Zandieh, A.
117. Shallow and Deep Shear-wave Velocity Data for ShakeMaps, Characterizations of Earthquake Recording Station Sites and Site Response Analyses in Washington and Oregon. **Cakir, R.**, Walsh, T. J., Hayashi, K., Xia, J., and Madin, I.
118. Computation of H/V Spectral Ratios at Sites with Strong Lateral Heterogeneity Using Diffuse Field Theory and IBEM. **Molina Villegas, J. C.**, Perton, M., and Sanchez Sesma, F. J.
119. Validation of Dynamic Site Soil Profile at the Central United States Seismic Observatory, New Madrid Seismic Zone. **Brengman, C. M. J.**, Carpenter, N. S., Woolery, E. W., and Wang, Z.
120. Infinite Wedge Revisited: Scattering of Plane Waves by Wedge Topographic Features. Mohammadi, K. and **Assimaki, D.**

Thursday, 01 May – Concurrent SSA Oral Sessions

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity Session Chairs: Ivan Wong, Justin Rubinstein, and Thomas Braun (see page 461)	**Large and Damaging Earthquakes of 2013/2014** Session Chairs: Gavin Hayes, Thorne Lay, Harley Benz, and Charles Ammon (see page 465)	**Recent Advances in Ground Motions Simulation Methods and Their Validation** Session Chairs: Christine Goulet and Kim B. Olsen (see page 469)	**Alaska Update of the USGS National Seismic Hazard Maps** Session Chairs: Peter Haeussler, John Anderson, and Mark Petersen (see page 473)	**Monitoring Dynamic Changes at Active Volcanoes and Fault Zones** Session Chairs: Ninfa Bennington, Matt Haney, and Silvio de Angelis (see page 478)
8:30 AM	INVITED: Factors That Enhance the Likelihood of Fluid Injection-Induced Earthquakes Large Enough to be Felt. **McGarr, A.** and Rubinstein, J.	From Simple to Complex: Source Properties of Some Recent Large Earthquakes Using Seismic and Geodetic Data. **Hayes, G. P.**, Barnhart, W. D., Benz, H. M., Briggs, R. W., and Gold, R. D.	Three-Dimensional Ground-Motion Simulations of Earthquakes in the Hanford, Washington Area. **Frankel, A.**, Thorne, P., and Rohay, A.	INVITED: Challenges Facing the Update of the 2007 Probabilistic Seismic Hazard Map of Alaska and the Aleutians. **Wesson, R. L.**, Boyd, O. S., Mueller, C. S., and Frankel, A. D.	INVITED: Detecting Temporal Changes in Active Fault Zones during Large Earthquake Cycles. **Peng, Z.**
8:45 AM	The Curious Case of the Timpson, TX Earthquakes: Natural or Delayed Triggering? **Leidig, M.** and Bonner, J. L.	STUDENT: Coulomb Stress Changes Resulting from the Mw 7.7 2012 Haida Gwaii Earthquake. **Hobbs, T. E.**, Brillon, C., Cassidy, J. F., Dragert, H., and Dosso, S. E.	INVITED: Verification of Synthetic Near-Source Ground Motion against Empirical GMPE and Physics-Based Stochastic Source Characterization for Future Earthquakes. **Dalguer, L. A.**, Baumann, C., and Song, S. G.	Updating the USGS Seismic Hazard Maps for Alaska. **Mueller, C. S.**, Wesson, R. L., Boyd, O. S., Bufe, C. G., Frankel, A. D., and Petersen, M. D.	INVITED: Imaging Dynamic Changes in Heterogeneous Structures Using Diffuse Waves: From Theory to Applications. **Planés, T.**, Obermann, A., Larose, E., Campillo, M., Rossetto, V., Margerin, L., and Froment, B.
9:00 AM	INVITED: Trying to Discriminate Triggered from Natural Seismicity: Three Case Studies from Northern Italy. **Braun, T.**, Cesca, S., and Dahm, T.	Investigating Dynamic Interactions between the October 2012 Haida Gwaii and January 2013 Craig Earthquakes. **Walter, J. I.**, Kao, H., Peng, Z., Aiken, C., Meng, X., and Zimmerman, J.	Summary of a Large Scale Validation Project Using the SCEC Broadband Strong Ground Motion Simulation Platform. **Goulet, C. A.** and BBP Validation Group.	INVITED: The Denali Fault Slip Rate and Models of Interior Alaska Active Deformation. **Haeussler, P. J.**, Matmon, A., Schwartz, D. P., and Seitz, G.	INVITED: Nonlinear Site Response in Medium Magnitude Earthquakes near Parkfield, California. **Rubinstein, J. L.**

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity. . .	**Large and Damaging. . .**	**Recent Adv-Gr Motion. . .**	**Alaska Update. . .**	**Monitoring Dynamic. . .**
9:15 AM	INVITED: The Azle, Texas, Earthquake Sequence of 2013–2014: Induced or Natural? **Ellsworth, W. L.**, Benz, H. M., Cain, C., DeShon, H. R., Hayward, C., Luetgert, J. H., Quitoriano, V., Stump, B., and Wald, D. J.	Magnitude 7.5 Earthquake of 5 January 2013 on Queen Charlotte Fault in Southeast Alaska. **Ruppert, N. A.**, Yue, H., and Freymueller, J. T.	INVITED: Site-Specific Response in Validation Studies of Physics-Based Earthquake Simulations. **Assimaki, D.**, Shi, J., and Taborda, R.	Recurrence of Large Earthquakes along the Denali Fault System. **Schwartz, D. P.**, Haeussler, P. J., Seitz, G. G., Koehler, R. D., Personius, S. F., Crone, A. J., and Dawson, T. E.	4D Reflection Monitoring of Deep Magma: Lessons from the SEA-CALIPSO Experiment. **Brown, L.** and Quiros, D.
9:30 AM	Characterization of an Earthquake Sequence Triggered by Hydraulic Fracturing in Harrison County, Ohio. **Friberg, P. A.**, Besana-Ostman, G. M., and Dricker, I.	STUDENT: Seismic Slip Distribution of Large Inter- and Intra- Plate Oceanic Strike-slip Earthquakes. **Aderhold, K.**, Abercrombie, R. E., and Antolik, M.	INVITED: Some Modifications to Parameters Used in the Stochastic Method for Simulating High-Frequency Ground Motions. **Boore, D. M.** and Thompson, E. M.	Synthesis of Results from a Transect of Paleoseismic Investigations across the Alaska Range. **Bemis, S. P.**, Walker, L. A., Federschmidt, S., DeVore, J. R., and Taylor, T. P.	Three-Dimensional Velocity Structure of the Galeras Volcano (Colombia) from Local Earthquake Tomography and Evolution of the Volcanic Activity. **Vargas Jimenez, C. A.** and Torres, R.
9:45–10:45 AM	Break & Posters – Cook & Arteaga				
10:45 AM	INVITED: Triggered Earthquakes Far from the Wellbore: Fluid Pressure Migration and the 2008–2014 Jones Swarm, Central Oklahoma. **Keranen, K. M.**, Weingarten, M., Bekins, B., Ge, S., and Abers, G. A.	How the 2013 Lushan Earthquake (Ms = 7.0) Triggered Its Aftershocks: Insights from Static Coulomb Stress Change Calculations. **Zhu, S.**, Miao, M., Ren, J., and Shi, Y.	INVITED: Comparison of 3D and 1D Wave Propagation Modeling in the San Francisco Bay Area. **Pitarka, A.**, Rodgers, A. J., Petersson, A., and Sjogreen, B.	Implications of Recent Paleoseismic Observations for Models of Alaska-Aleutian Megathrust Rupture Patterns. **Briggs, R. W.**, Witter, R. C., Nelson, A. R., Koehler, R. D., Haeussler, P. J., Engelhart, S. E., Gelfenbaum, G., Dura, T., and Carver, G.	STUDENT, INVITED: Changes in Seismic Velocity during the 2004–2008 Eruption of Mount St. Helens Volcano. **Hotovec-Ellis, A. J.**, Vidale, J. E., Gomberg, J. S., Moran, S., and Thelen, W. A.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity. . .	**Large and Damaging. . .**	**Recent Adv-Gr Motion. . .**	**Alaska Update. . .**	**Monitoring Dynamic. . .**
11:00 AM	INVITED: Potential Case of Induced Seismicity from a Water Disposal Well in South-Central Oklahoma. **Holland, A. A.**	Rupture History of the 2013 Mw6.8 Lushan, China Earthquake Based on Strong Motion Data Inversion: A High-Angle Blind Thrusting Event. **Zhang, G.**, Hetland, E. A., Shan, X., and Vallee, M.	The Shakeout Earthquake Scenario with Plasticity. **Roten, D.**, Olsen, K. B., Day, S. M., Cui, Y., and FAh, D.	GPS-Derived Fault Geometries and Slip Rates for Eastern Prince William Sound and the St. Elias Orogen. **Elliott, J.**, Freymueller, J. T., and Larsen, C. F.	STUDENT, INVITED: Observations of Time-Lapsed Velocity Changes at Yellowstone from Ambient Noise Correlation Functions. **Seats, K. J.** and Lawrence, J. F.
11:15 AM	Constraints on Recent Earthquake Source Parameters, Fault Geometry and Aftershock Characteristics in Oklahoma. **McNamara, D. E.**, Benz, H. M., Herrmann, R. B., and Bergman, E. A.	STUDENT: Rupture Process of the November 17, 2013 M_w 7.8 Scotia Sea Earthquake. **Ye, L.**, Lay, T., Koper, K. D., Smalley, R., Bevis, M. G., Zakrajsek, A. F., and Teferle, F. N.	PRENOLIN Project: A Benchmark on Numerical Simulation of 1-D Non-Linear Site Effect. 2 – Preliminary Results from the Verification Phase on Idealistic Cases. **Régnier, J.**, Bonilla, L. F., bard, P. Y., Bertrand, E., Hollender, F., Kawase, H., Sicilia, D., the PRENOLIN participants: D. Assimaki, D. Boldini, S. Iai, S. Kramer, E. Foerster, C. Gélis, G. Gazetas, J. Gingery, Y. Hashash, P. Moczo, S. Foti, G. Lanzo, F. Lopez-Caballero, D. Roten, K. Pitilakis, F. DeMartin, B. Jeremic, A. Nieto-Ferro, M.P. Santisi, and D. Mercerat	INVITED: The Castle Mountain Fault, South-Central Alaska: Sense of Slip and Slip Rate. **Koehler, R. D.** and Reger, R. D.	Dynamics of the Yellowstone Volcanic System Using 4-D Seismic Imaging. **Farrell, J.**, Smith, R. B., and Lin, F. C.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity. . .	**Large and Damaging. . .**	**Recent Adv-Gr Motion. . .**	**Alaska Update. . .**	**Monitoring Dynamic. . .**
11:30 AM	INVITED: The 2013 Seismic Sequence Close to the Gas Injection Platform of the Castor Project, Offshore Spain. **Cesca, S.**, Grigoli, F., Heimann, S., Gonzalez, A., Maghsoudi, S., Buforn, E., Blanch, E., and Dahm, T.	The Implosive Component of the 2013 Okhotsk Sea Deep Earthquake: Evidence from Radial Modes and Constraints from Geodetic Data. **Okal, E. A.**, Saloor, N., Freymueller, J. T., Steblov, G. M., and Kogan, M. G.	Rupture Dynamics and Ground Motions from 3-D Dynamic Rough-Fault Simulations of Dip-Slip Events. **Shi, Z.** and Day, S. M.	New Seismic Hazard Model for Northwestern Canada. **Allen, T. I.**, Adams, J., Rogers, G. C., and Halchuk, S.	Monitoring Changes in Seismic Velocity Related to Magmatism at Okmok and Redoubt Volcanoes, Alaska. **Bennington, N. L.**, Haney, M., De Angelis, S., and Thurber, C. H.
11:45 AM	Seismic Response to Power Production at the Coso and Salton Sea Geothermal Fields, Southeastern CA: Using Operational Parameters and Relocated Events to Study Anthropogenic Seismicity Rates and Reservoir Scale Tectonic Structure. **Lajoie, L. J.**, O'Connell, D. R. H., Brodsky, E. E., and Creed, R. J.	Slip Models for the 2013 M7.7 and M6.8 Balochistan Earthquakes in Pakistan. **Fielding, E. J.**, Wei, S. J., Yague-Martinez, N., Leprince, S., Hudnut, K. H., Khan, S. D., Motagh, M., Ayoub, F., and Samsonov, S.V.	STUDENT: High-Complexity Deterministic Q(f) Simulation of the 1994 Northridge Mw 6.7 Earthquake. **Withers, K. B.**, Olsen, K. B., Shi, Z., and Day, S.	Site-Specific Probabilistic Seismic Hazard Analyses of Anchorage, Alaska and Comparison to the 2007 National Seismic Hazard Maps. **Wong, I.**, Zachariasen, J., and Dober, M.	STUDENT: Imaging Seismic Source Variations with Back-Projection Methods at Sierra Negra Volcano, Galapagos Islands. **Kelly, C. L.**, Lawrence, J. F., and Ebinger, C.
Noon–1:15 PM	Lunch – La Perouse				

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity *(continued)*	**Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)** Session Chairs: Jim Mori, David Wald, and Emily C. Roland (see page 467)	**Recent Advances in Ground Motions Simulation Methods and Their Validation** *(continued)*	**Seismic Imaging as USArray Moves to Alaska** Session Chairs: Carene Larmat, Frank Vernon, Bob Woodward, and Lindsay Worthington (see page 475)	**Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications** Session Chairs: Sanaz Rezaeian, Christine Goulet, John Anderson, and Mark Petersen (see page 480)
1:30 PM	STUDENT: Induced Seismicity Mechanisms at The Geysers Geothermal Field from the Analysis of Stress Field Variations Related to Fluid Injection. **Martínez-Garzón, P.**, Kwiatek, G., Bohnhoff, M., Dresen, G., and Hartline, C.	INVITED: Low Coseismic Friction on the Tohoku Fault Determined from Temperature Measurements. **Fulton, P. M.**, Brodsky, E. E., Kano, Y., Mori, J., Chester, F., Ishikawa, T., Harris, R. N., Lin, W., Eguchi, N., Toczko, S., Expedition 343, 343T, and KR13-08 Scientists	Using Attenuation in Ground Motion Prediction Equations: Validating Improvements to Strong Ground Motion Predictions. **Pasyanos, M. E.**	Seismic Velocity Structure and Anisotropy of the Alaska Subduction Zone Derived from Surface Wave Tomography. Wang, Y. and **Tape, C.**	INVITED: The 2014 Update of the United States National Seismic Hazard Models. **Petersen, M.**, Moschetti, M., Powers, P., Mueller, C., Haller, K., Frankel, A., Zeng, Y., Rezaeian, S., Harmsen, S., Boyd, O., Field, N., Chen, R., Rukstales, K., Luco, N., Wheeler, R., Williams, R., and Olsen, A.
1:45 PM	Geomechanical Reservoir Characterization Using Induced Seismicity and State-of-The-Art Waveform Processing Techniques. **Kwiatek, G.**, Bohnhoff, M., Martínez-Garzón, P., Bulut, F., and Dresen, G.	INVITED: Stress State near Updip End of the 2011 Tohoku-Oki Earthquake Inferred from OBS Aftershock Observations. **Obana, K.**, Kodaira, S., Hino, R., and Shinohara, M.	Constraining GMPEs in Critical Ranges for Complex Ruptures Using Strong Motion Simulation Procedures on the SCEC Broadband Platform. **Bayless, J.**, Dreger, D., Wooddell, K., Abrahamson, N., and Donahue, J.	INVITED: Seismic Imaging along a Dense Broadband Transect through Central Alaska. **Abers, G. A.** and Christensen, D. H.	INVITED: Recommendations for Future Updates of the National Seismic Hazard Maps. **Anderson, J. G.**, Abrahamson, N. A., Campbell, K. W., Chapmann, M., Hamburger, M. W., Lettis, W. R., Shome, N., Weldon II, R. J., and Wills, C. J.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity. . .	**Great Earthquakes. . .**	**Recent Adv-Gr Motion. . .**	**Seismic Imaging as USArray. . .**	**Dev of 2014 Hazard Maps. . .**
2:00 PM	Moment Tensor Dynamics of Hydraulic Fracturing in Hydrocarbon Reservoirs. **Baig, A. M.** and Urbancic, T. I.	Large Shallow Slip of the 2011 Tohoku-oki Earthquake. **Mori, J.** 30 minutes	STUDENT: The Effect of Topography on the Seismic Wavefield. **Cahayani, U.** and Tape, C.	Imaging the Megathrust Zone and Yakutat/Pacific Plate Interface in the Alaska Subduction Zone. **Kim, Y.**, Abers, G. A., Li, J., Christensen, D., Calkins, J., and Rondenay, S.	The 2014 National Seismic Hazard Maps: Updated Catalogs and Seismicity Models. **Mueller, C. S.**
2:15 PM	INVITED: Seismic Hazard and Ground Motion Implications of Induced Seismicity. **Atkinson, G. M.**	Large Shallow Slip of the 2011 Tohoku-oki Earthquake. **Mori, J.** *(continued)*	Long-Period Ground Motion Simulation for the 2007 Chuetsu-oki, Japan, Earthquake Using the Ambient Seismic Field. **Miyake, H.**, Denolle, M. A., and Beroza, G. C.	INVITED: Seismic Tomography of Alaskan Volcanoes: Accomplishments and Opportunities. **Thurber, C.**, Zhang, H., Prejean, S., Haney, M., Ohlendorf, S., Lemon, S., and Brown, J.	Ground Motion Models Used in the 2014 U.S. National Seismic Hazard Maps. **Rezaeian, S.**, Petersen, M. D., Moschetti, M. P., Powers, P., Harmsen, S. C., and Frankel, A. D.
2:30 PM	INVITED: Quantifying the Seismic Hazard From Natural and Induced Earthquakes. **Rubinstein, J. L.**, Llenos, A., Ellsworth, W. L., McGarr, A., Michael, A., Mueller, C., and Petersen, M.	Constraining the Broadband Slip History of 2011 Tohoku Earthquakes Using a Two-Step Finite Fault Approach. **Ji, C.** and Archuleta, A. J.	STUDENT: Validation of the Equivalent Point-Source Method for Modeling Ground Motions from Large Earthquakes. **Yenier, E.** and Atkinson, G. M.	Seismicity of Alaska 1973–2013: A Well-constrained Catalog of Earthquake Locations Using Multiple Event Relocation Methods. Benz, H., Myers, S., Johannesson, G., Bergman, E., **Earle, P.**, and Hayes, G.	INVITED: New Time-Independent and Time-Dependent Seismic Source Models for the Wasatch Front, Utah for the National Seismic Hazard Maps. **Wong, I.**, Lund, W., DuRoss, C., Thomas, P., Arabasz, W., Crone, A., Hylland, M., Luco, N., Olig, S., Pechmann, J., Personius, S., Petersen, M., Schwartz, D., and Smith, R.
2:45–3:45 PM	Break & Posters – Cook & Arteaga				

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity *(continued)*	**Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)** *(continued)*	**Merging Paths: Earthquake Simulations and Engineering Applications** Session Chairs: Ricardo Taborda, Aysegul Askan, and Tsuyoshi Ichimura (see page 472)	**Seismic Imaging as USArray Moves to Alaska** *(continued)*	**Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications** *(continued)*
3:45 PM	INVITED: Managing Seismic Hazard Due to Induced Earthquakes in Central Arkansas through Partnership between Scientific and Regulatory Agencies. **Horton, S. P.**, Ausbrooks, S. M., Withers, M. M., and Ogwari, P. O.	INVITED: Constraining Shallow Slip and Tsunami Excitation in Megathrust Ruptures Using Seismic, Ocean Acoustic, and Tsunami Waves Recorded on Ocean-Bottom Sensor Networks. **Dunham, E. M.**, Kozdon, J. E., and Lotto, G. C.	Simulation of Structure Seismic Response Based on Analyzing Fault-structure System in Large Computing Environment. **Quinay, P. E. B.**, Ichimura, T., and Hori, M.	Tracking Glaciers with the Alaska Seismic Network. **West, M. E.**	Integrating UCERF3 into the 2014 National Seismic Hazard Maps. **Powers, P.** M. and Field, E. H.
4:00 PM	Protocol and Best Practices for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems (EGS). Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., and **Wong, I.**	Complete Stress Drop in Shallow Great Earthquakes. **Hardebeck, J. L.**	End-to-End Simulation of the Response of Building Clusters during Earthquakes in the Presence of Coupled Soil-Structure Interaction Effects. **Taborda, R.**, Isbiliroglu, Y., and Bielak, J.	STUDENT: Automated Surface Wave Phase Velocity Measuring System and Its Application on USArray. **Jin, G.** and Gaherty, J.	INVITED: A Summary of Findings and Models of the NGA-West2 Research Program. **Bozorgnia, Y.**, Abrahamson, N., Campbell, K., Rowshandel, B., and Shantz, T.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	Induced Seismicity. . .	**Great Earthquakes. . .**	**Merging Paths. . .**	**Seismic Imaging as USArray. . .**	**Dev of 2014 Hazard Maps. . .**
4:15 PM	Discussion	Seismic Versus Aseismic Slip: Probing Mechanical Properties of the Northeast Japan Subduction Zone. **Shirzaei, M.**, Bürgmann, R., Uchida, N., Hu, Y., and Pollitz, F.	City-Soil Interaction in the Valley of Mexico: Amplification and Long Duration Ground Motion. **Ramirez-Guzman, L.**, Macias Castillo, M., Contreras, M., Zepeda, O., and Aguirre, J.	Resurrection Plate Revisited: Does a New Kinematic Model of the Yakutat, Crescent, and Siletz Terranes Solve an Old Puzzle? **McCrory, P. A.** and Wilson, D. S.	Proposed Earthquake Ground Motion Maps for Model Building Codes Based on the 2014 United States Geological Survey National Seismic Hazard Model. Luco, N., Bachman, R. E., Crouse, C. B., Harris, J. R., Hooper, J. D., and Kircher, C. A., (**Rezaeian, S.**)
4:30 PM		CMT Re-analysis of the Great 1964 Alaska Earthquake. **Nettles, M.** and Ekström, G. 30 minutes	STUDENT: Nonlinear Time History Analyses of Structures under Real and Synthetic Ground Motions. **Karimzadeh, S.**, Askan, A., Yakut, A., and Ameri, G.	Lithospheric Modification at the Southern Edge of Laurentia Revealed by Broadband Seismology. **Pulliam, J.**, Grand, S. P., and Gurrola, H.	On NGA and NEHRP Site Coefficients Inferred for Site Classes in U.S. Building Codes. **Borcherdt, R. D.**
4:45 PM			Rupture to Rafters to Response: Completing the Loop of Earthquake Science, Engineering and Policy. **Lin, T.**	Attenuation and Shear-Wave Speed Tomography in the Central U.S. from Teleseismic Ambient Seismic Field Correlations. **Poli, P.** and Prieto, G. A.	Preliminary Application of the 2014 U.S. National Seismic Hazard Map and Its Implication in the Reinsurance Industry. **Lee, S. W.** and Wang, Z.
5:15–6:15 PM	Joyner Lecture - Alaska Ballroom, Hilton (see page 482)				
	Ground Motion Prediction Equations: Past, Present, and Future Boore, D. M.				

Thursday, 01 May – Morning Poster Sessions

Alaska Update of the USGS National Seismic Hazard Maps
(see page 482)

1. Earthquake Risk in Alaska. **Nyst, M.**, Williams, C., and Fitzenz, D.
2. Preliminary Results from the Watana Seismic Network and Development of a 3D Slab Model, South-Central Alaska. **LaForge, R.**, Ostenaa, D., Shumway, A., Turner, J., Lajoie, L., Ruppert, N., Carey, B., and Bruen, M.
3. Slip on the Suckling Hills Splay Fault during the 1964 Alaska Earthquake. Chapman, J. B., **Elliott, J.**, Doser, D. I., and Pavlis, T. L.
4. Creation of the Alaska Earthquake Scenario Atlas: Using ShakeMap to Improve Awareness of Seismic Hazard and Risk in the Last Frontier. **Gardine, M.**, Ruppert, N., West, M. E., Wald, D., Quitoriano, V., and Worden, B.
5. Estimating Mmax of Intraslab Earthquakes. Shumway, A. M., **Reyes, D. K.**, and LaForge, R.

Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications
(see page 483)

6. NGA-West2 Horizontal Ground Motion Model: Comparison of CB08 and CB14. **Campbell, K. W.** and Bozorgnia, Y.
7. Alternative Approaches for the National Seismic Hazard Mapping. **Wang, Z.** and Cobb, J.
8. A Fault-Based Model for Crustal Deformation in the Western United States and Its Application to Seismic Hazard Analysis. **Zeng, Y.** and Shen, Z. K.
9. Update of the Pacific Northwest Fault and Ground-motion Models for the 2014 National Seismic Hazard Maps. **Petersen, M. D.**, Frankel, A. D., and Chen, R.
10. Effect of Adaptive Smoothing Seismicity Rate Models on Seismic Hazard in the 2014 Update to the U.S. National Seismic Hazard Maps. **Moschetti, M. P.**, Powers, P., Felzer, K., and Petersen, M.
11. Implications of Recent Findings from Bayesian Inversion of GPS Data for Seismic Hazard Assessment in California. **Murray, J. R.** and Minson, S. E.
12. Probabilistic Tsunami Hazard Mapping. **Thio, H. K.**, Polet, J., Li, W., Wilson, R., and Somerville, P.
13. Ground Motion Attenuation Relations for Central U.S. Using Hybrid Broadband Synthetics. **Shahjouei, A.** and Pezeshk, S.

Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)
(see page 485)

14. Could a Sumatra-Like Megathrust Earthquake Occur in the South Ryukyu Subduction Zone? **Lin, J. Y.**, Sibuet, J. C., Hsu, S. K., and Wu, W. N.
15. Can Compaction Further Enhance Inelastic Wedge Failure in Shallow Subduction Zone Earthquakes? **Hirakawa, E. T.** and Ma, S.
16. A Joint Seismic and Geodetic Rupture Model for the 2012 Haida Gwaii Earthquake and the Location of Slip on the Interface Relative to the Queen Charlotte Fault. **Polet, J.**, Simons, M., Fielding, E. J., and Samsonov, S. V.
17. Relationship between High-frequency Radiation and Asperity Rupture, Revealed by Hybrid Back-projection with Non-planer Fault. **Okuwaki, R.**, Yagi, Y., and Hirano, S.
18. The Occurrence of Two Types of Megathrust Earthquakes in South Central Alaska. **Reeder, J. W.**

Induced Seismicity
(see page 486)

19. Characteristics of Induced/Triggered Earthquakes during The Guy-Greenbrier Earthquake Sequence (2010–2011) in North-Central Arkansas. **Ogwari, P. O.**, Horton, S. P., and Ausbrooks, S. M.
20. Earthquake Monitoring in Eastern Canadian Areas with Shale Gas Exploration Potential. **Lamontagne, M.**
21. Seismic Monitoring at the Decatur, IL, Carbon Dioxide Sequestration Demonstration Site. **McGarr, A.**, Kaven, J. O., Hickman, S. H., Walter, S. R., Svitek, J., and Ellsworth, W. L.
22. Microseismic Network Performance Estimation: Comparing Predictions to an Earthquake Catalogue. Greig, D. W. and **Ackerley, N. J.**
23. Spatio-Temporal Evolution of Earthquake Clusters in Natural and Induced Seismicity. **Zaliapin, I.** and Ben-Zion, Y.
24. Geothermal Pumping and Induced Seismicity in California Geothermal Fields. **Weiser, D. A.**, Jackson, D. D., and Jones, L. M.
25. Precision and Accuracy of Micro-Seismic Event Locations. **Myers, S. C.**, Johannesson, G., Templeton, D. C., and Matzel, E. M.
26. Examining Induced Seismicity in SE New Mexico in the Vicinity of the Waste Isolation Pilot Plant. **Edel, S. S.**, Bilek, S. L., and Ingate, S. F.
27. Source Characteristics and Failure Process of Hydraulic Fracturing Micro-Seismic Events Located within and Below the Target Formation. **Viegas, G.** and Urbancic, T.

28. Comparison of Empirical and Model-Based Matched Field Processing (MFP) Earthquake Detection Techniques at the Newberry EGS Site. **Templeton, D. C.**, Matzel, E. M., and Harris, D. B.
29. Seismic Efficiency, Overshoot and Enhanced Dynamic Weaking of Fractures Associated with Stimulation in Heavy Oil Reservoirs. **Meighan, L. N.**, Urbancic, T. I., and Baig, A. M.
30. A Study of the Potential for Induced Seismicity Resulting from CO2 Injection at Kimberlina, Southern San Joaquin Valley, California. **Bradley, C. R.**, Lee, R. C., Coblentz, D. C., Wilson, J. E., and Stone, I. P.
31. Characterizing Potentially Induced Earthquake Rate Changes in the Brawley Seismic Zone, CA. **Llenos, A. L.** and Michael, A. J.
32. Extreme Shallow Earthquakes in the Sedimentary Basin of Imperial Valley, Triggering of Extensional Faulting by Fluid Injection. **Wei, S.**, Hudnut, K., Andrea, D., Parker, J. W., Graves, R., Helmberger, D. V., Fielding, E. J., and Liu, Z.
33. Estimation of Seismic Hazard Due to Induced Seismicity Related to Deep Geothermal Wells. **Spies, T.**, Schlittenhardt, J., Kopera, J. R., and Morales, W.

Large and Damaging Earthquakes of 2013/2014
(see page 489)

34. The ISC Event Bibliography: A Useful Service for Studying Notable Seismic Events. **Di Giacomo, D.**, Storchak, D. A., Safronova, N., Ozgo, P., and Harris,
35. Possibility of the Independence between the 2013 Lushan Earthquake and the 2008 Wenchuan Earthquake on Longmen Shan fault, Sichuan, China. **Jia, K.**, Zhou, S., Zhuang, J., and Jiang, C.
36. Near Field Dynamic, Co-seismic and Post-seismic Deformations Associated with the 2013, M7.8, and 2003, M7.6, South Scotia Ridge Earthquakes Observed with GPS. **Smalley, R.**, Bevis, M. G., Zakrajsek, A. F., Teferle, F. N., Dalziel, I. W. D., Lawver, L. A., and Larter, R. D.
37. Characterization of Recent Large Earthquakes in Asia from Backprojection Imaging of Regional Seismic Data. **Euler, G. G.**, Randall, G. E., and Hartse, H. E.
38. Mainshock and Aftershock Mechanisms of the $M_w = 7.5$ Craig, Alaska Earthquake of January 5, 2013 from Continuous Moment Tensor Scanning. **Macpherson, K. A.**, Ruppert, N. A., Dreger, D. S., Lombard, P., Freymueller, J. T., Nicolsky, D. J., and Guilhem, A.
39. Modeling Large Earthquakes in Realistic Structures; Mw8.3 Sea of Okhotsk Earthquake. **Wei, S. J.**, Helmberger, D. V., and Sun, D. Y.
40. Puerto Rico M6.4 Earthquake of January 13, 2014: PGA & IMM Distribution in the Island. **Huerta-Lopez, C.**, Martinez-Pagan, J., Santana-Torres, E., Upegui-Botero, M., and Martinez-Cruzado, J.
41. Response and Fault Characteristics of the Mw6.4 January 13, 2014 Puerto Rico Earthquake: The Largest Event Recorded at the Puerto Rico Seismic Network. **Lopez-Venegas, A. M.**, Martinez, F., Mattioli, G. S., Huerfano, V., Baez, G., Irizarry, H., and von Hillebrandt, C.

Merging Paths: Earthquake Simulations and Engineering Applications
(see page 491)

42. Hybrid Low-High Frequency Ground motion Time Histories for Central U.S. **Shahjouei, A.** and Pezeshk, S.
43. Synthetic Strong Ground Motion from a Scenario Earthquake in a Region of Sparse Seismological Data: Xanthi, N. Greece. **Roumelioti, Z.**, Margaris, B., and Kiratzi, A.
44. The Ambient Seismic Field Captures Complex Sedimentary Basin Effects. **Denolle, M. A.**, Miyake, H., Nakagawa, S., Hirata, N., and Beroza, G. C.
45. Ground Motion Similarity and Coherency between Total and Effective Stress Analyses. **Montoya-Noguera, S.** and Lopez-Caballero, F.
46. Developing Ground Motions for Tall Buildings in Southern California. **Zafir, Z.**

Monitoring Dynamic Changes at Active Volcanoes and Fault Zones
(see page 492)

47. Ambient Noise Monitoring of Temporal Changes in Seismic Velocity at the Geysers Geothermal Field, California. **Lai, V. H.**, Taira, T., and Dreger, D. S.
48. Nonlinear Deformation Examples Recorded by the Plate Boundary Observatory. **Puskas, C. M.**, Phillips, D., Hodgkinson, K., Berglund, H., Sievers, C., Meertens, C. M., Mattioli, G. S., and Mencin, D.
49. Study of the Site Effects at Cotopaxi Volcano: Construction of a Seismic Activity Index. **Ortiz, H. D.**, Palacios, P. B., and Ruiz, M. C.
50. Explosion Earthquakes during the 2007 Eruption of Pavlof Volcano, Alaska. **Smith, C. M.** and McNutt, S. R.
51. Receiver Function Analyses of Uturuncu Volcano, Bolivia. **McFarlin, H.**, Christensen, D., Thompson, G., and McNutt, S.

Network Operations and Data Centers
(see page 493)

52. Datasets for Seismology: ISC, EHB and GT Bulletins, Station Registry, ISC-GEM Catalogue and Event Bibliography. **Storchak, D. A.**, Di Giacomo, D., Richardson, W. P., and Harris, J.

53. Field Observation and Quality Control of China Array Project. **Yuan, S. Y.**, Yang, W., Song, L. L., Wang, B. S., Xu, W. W., Liu, Z. Y., Jia, Y. H., and Qiao, S.
54. Croatian Seismicity Database. **Herak, M.**, Herak, D., and Ivanèi, I.
55. The Next Generation of Data Flow at the USGS National Earthquake Information Center (NEIC). **Guy, M.**, Patton, J., Ketchum, D., Fee, J., Martinez, E., Hearne, M., Benz, H., and Earle, P.
56. The Mexican Seismic Network. **Alcantara, L.**, Ramirez-Guzman, L., Valdes, C., Perez, C., Perez, J., and Almora, D.
57. Advanced National Seismic System (ANSS) Comprehensive Catalog. **Fee, J. M.**, Martinez, E. M., Hunter, E. J., Hearne, M., and Guy, M.
58. A New Shallow Water Cabled OBS Network Off Central California. **McLaren, M. K.** and Rademacher, H.
59. Remote Calibration Procedures for STS-2s: Example from the STS-2HG for CTBTO at YBH. **Hellweg, M.**, Uhrhammer, R. A., and Taira, T.
60. Large Scale Real-Time GPS Networks, Data Processing Systems and Community Datasets. **Phillips, D. A.**, Mencin, D. J., Sievers, C., Austin, K., Berglund, H. T., Blume, F., Meertens, C. M., and Mattioli, G. S.
61. Automatically Processed Aftershock Sequence for the 2012 Oct 27 Haida Gwaii Earthquake. **Mulder, T. L.**, Vernon, F. L., Rosenberger, Kilb, White, M. C., Rogers, G. C., Brillon, C., and Bentkowski, W.
62. Need Data? The IRIS DMC Can Help. **Trabant, C.**, Ahern, T., Casey, R., Reyes, C., Suleiman, Y., Weertman, B., and Benson, R.

New Insights into Ground Failure as an Urban Earthquake Hazard
(see page 495)

63. Mapping Earthquake Induced Liquefaction Surface Effects from the 2011 Tohoku Earthquake Using Satellite Imagery. **Zhu, J.**, Baise, L. G., Koch, M., and Gaber, A.
64. The Age of Landslides in Anchorage, Alaska. **Reeder, J. W.**
65. Landslide Hazard Mapping and Quantitative Landslide Hazard Planning Scenario for Aizawl, India. **Clahan, K. B.** and Dee, S.
66. Influence of Near Surface Stiffness, Material Type, and Prior Rupture History on Reverse Fault Surface Rupture. Stanton, K. V. and **Moss, R. E. S.**
67. Updated Geospatial Liquefaction Model for Global Use. **Zhu, J.**, Baise, L. G., Thompson, E. M., Magistrale, H., and Wald, D. J.

Recent Advances in Ground Motions Simulation Methods and Their Validation
(see page 496)

68. Using the SCEC Broadband Platform for Strong Ground Motion Simulation and Validation. **Silva, F.**, Maechling, P., Goulet, C., Somerville, P., and Jordan, T.
69. Evaluation of the Point-Source Stochastic Simulation Method within the SCEC Broadband Platform Validation Effort. **Di Alessandro, C.**, Boore, D. M., and Abrahamson, N. A.
70. Validation of the Stochastic Finite Fault Module (EXSIM) Implemented on the SCEC Broadband Platform. **Assatourians, K.** and Atkinson, G.
71. Refinements to the Graves and Pitarka (2010) Broadband Simulation Method. **Graves, R. W.**
72. The SDSU Broadband Ground Motion Generation Module Version 1.5. **Olsen, K. B.** and Takedatsu, R.
73. Adapting the Composite Source Model for the SCEC Broadband Platform. **Anderson, J. G.**
74. Separating Low- and High-Frequency Wave Propagation in Synthetic Broadband Ground Motion Modeling. **Crempien, J. G. F.** and Archuleta, R. J.
75. Pseudo-dynamic Source Modeling with 1-Point and 2-Point Statistics of Earthquake Source Parameters. **Song, S. G.**, Dalguer, L. A., and Mai, P. M.
76. Broadband Acceleration Time Histories Synthesis by Coupling Low Frequency Seismic Noise and High Frequency Stochastic Modelling. **Viens, L.**, Laurendeau, A., Bonilla, L. F., and Shapiro, N.
77. Deterministic Simulation of the Mw 5.4 Chino Hills Event with Frequency-Dependent Attenuation, Heterogeneous Velocity Structure and Realistic Source Model. **Savran, W. H.** and Olsen, K. B.
78. Sensitivity of Ground Motion Simulation Validation Criteria to Filtering. **Khoshnevis, N.** and Taborda, R.
79. 3D Modeling of Full Waveform Propagation to Evaluate Site Effects on Design Ground Motions at LANL. **Larmat, C. S.**, Miller, T. A., Gable, C. W., and Lee, R. C.
80. Two Summation-By-Parts Finite Difference Codes for Large Scale Simulations of Seismic Motion. **Petersson, N. A.**, Sjogreen, B., and Rodgers, A. J.
81. A New Discrete Representation of Heterogeneous Medium for the Staggered-grid Finite-difference Modelling of Earthquake Motion. Kristek, J., **Moczo, P.**, Chaljub, E., De Martin, F., Kristekova, M., and Galis, M.
82. GPU-based 3D Simulation of Acoustic Wave Propagation with Complex Topography. Kim, K. and **Lees, J. M.**

Seismic Imaging as USArray Moves to Alaska
(see page 499)

83. New Data Products at the IRIS DMC. Bahavar, M., Hutko, A., and **Trabant, C.**
84. EarthScope's Transportable Array in Alaska. **Busby, R. W.**, Hafner, K., and Woodward, R. L.
85. Celebrating 10 Years of Delivering EarthScope USArray Transportable Array data from the Array Network Facility (ANF). Eakins, J. A., **Vernon, F. L.**, Astiz, L., Davis, G. A., Meyer, J., Reyes, J., Martynov, V., Tytell, J., and Cox, T.A.
86. Flat-Slab Subduction and Whole Crustal Faulting in Alaska: Potential Targets for Earthscope and Joint Active-Passive Seismic Imaging. **Worthington, L. W.**, Gulick, S. P. S., Christeson, G., van Avendonk, H. J. A., Pavils, G. L., Ruppert, N., and Pavlis, T. L.
87. Joint Inversion of Seismic and Gravity Data for Velocity Structure and Hypocentral Locations at Akutan and Makushin Volcanoes. **Syracuse, E. M.**, Maceira, M., and Zhang, H.
88. Using S Receiver Functions to Investigate Lithospheric and Crustal Structure Below Alaska. **O'Driscoll, L. J.** and Miller, M. S.
89. Waveform Modeling of Large Earthquakes of the Southern Fairbanks Seismic Zone, Alaska (1929–1947). **Doser, D. I.**
90. Seismic Moment Tensors in Southern Alaska Derived from Body Waves and Surface Waves. **Silwal, V.** and Tape, C.
91. Earthquakes of the Minto Flats Seismic Zone, Central Alaska. **Keyson, L.**, Silwal, V., West, M., and Tape, C.
92. Crustal Thickness beneath the Western United States from Virtual Deep Seismic Sounding (VDSS). **Yu, C. Q.**, van der Hilst, R. D., and Chen, W. P.
93. The Wyoming Province and the Llano Province: A Tale of Two Proto-continents. **Porritt, R. W.**, Allen, R. M., Pollitz, F. F., and Miller, M. S.
94. Application of Advanced Multivariate Inversion Techniques to the Western U.S. **Maceira, M.**, Ammon, C. J., Chai, C., and Herrmann, R. B.
95. Arc Structure around Mount Rainier From the Joint Inversion of Receiver Functions and Seismic Noise. **Obrebski, M.**, Abers, G., and Foster, A.
96. A Joint Local, Regional and Teleseismic Tomography Study of the New Madrid Seismic Zone. **Nyamwandha, C. A.**, Powell, C. A., and Langston, C. A.
97. Joint Inversion for Kilauea Volcano with an Edge-Preserving Constraint. **Lin, Y.**, Syracuse, E., Maceira, M., Larmat, C., and Zhang, H.
98. Low Wave Speed Zones in the Crust beneath the SE Tibet Revealed by Ambient Noise Adjoint Tomography. **Chen, M.**, Huang, H., van der Hilst, R. D., and Niu, F.
99. Which Receiver Function Features Warrant Geological Interpretation? **Lekic, V.** and Kolb, J. M.

Topics in Seismology: Hazards
(see page 503)

100. 3-D Dynamic Analysis of Precariously Balanced Rocks under Earthquake Excitation. **Veeraraghavan, S.** and Krishnan, S.
101. Performance of the North Anna Nuclear Power Plant during the 2011 Mineral, Virginia, Earthquake – A Regulatory Perspective. **Li, Y.**, Stirewalt, G. L., and Manoly, K. A.
102. The Impact of the L'Aquila Trial on the Scientific Community, An Update. **Braun, T.**, Amato, A., Cocco, M., Cultrera, G., Galadini, F., Margheriti, L., Nostro, C., Pantosti, D., Bonaccorso, A., Demartin, M., Marco De Martini, P., Di Stefano, R., Hunstad, I., Marzocchi, W., Meletti, C., Pacor, F., Pondrelli, S., Quareni, F., Selvaggi, G., and Todesco, M.
103. Using Fragile Geologic Features to Place Constraints on Long Term Seismic Hazard. **Stirling, M. W.**, Rood, D. H., and Barrell, D.
104. Defining the Usable Bandwidth for Response Spectra from Records with Different Sampling Rates and Anti-aliasing Filters. **Goulet, C. A.** and Boore, D. M.

Topics in Seismology: Processes
(see page 504)

105. Analysis of High-Frequency Icequakes at a Marine-Terminating Glacier in Greenland. **Veitch, S. A.** and Nettles, M.
106. The Response of Elastic Systems in the Earth to Dynamic Perturbations. **Delorey, A. A.**, Chao, K., Uchida, N., Obara, K., and Johnson, P. A.
107. Thermal Aging of the Oceanic Asthenosphere. **Paulson, E. M.** and Jordan, T. H.
108. Icequakes Triggered by Surface Waves From Large Teleseismic Earthquakes. **Peng, Z.**, Walter, J. I., Aster, R., Nyblade, A., Wiens, D., and Anandakrishnan, S.
109. Observations of Seismic Whistlers in USArray. **Young, B. A.** and Langston, C. A.
110. Permeability Evaluation According to Complex Precision Observations. **Besedina, A. N.**, Vinogradov, E. A., Gorbunova, E. M., and Kabychenko, N. V.

Topics in Seismology: Regional Seismicity and Tectonics
(see page 505)

111. Properties of the Subduction System in Mexico. **Kim, Y.** and Clayton, R. W.
112. The Significance of the Yakutat Plate to the Alaska Orocline. **Reeder, J. W.**
113. Seismicity in the Basin and Range Province of Sonora, México, near the Rupture of the 3 May 1887 Mw 7.5 Earthquake, between 2003 and 2011. **Castro, R. R.**
114. Seismic Studies of the Jalisco Block. **Escudero, C. R.**, Nuñez-Cornu, F. J., Gomez, A., Guitierrez, Q. J., Pinzon, J. I., Perez, O. G., Robles, F. J., and Cordoba, D.
115. Revisiting the Uljin Sequence of April 2006. **VanDeMark, T. F.**, Kim, T. S., and Kang, I. B.
116. Analysis on Co-seismic Responses of Well Water Level and Water Temperature in Ganshu Province to Wenchuan Ms8.0 Earthquake and Japan Ms9.0 Earthquake. **Zhang, Z.**, Wang, W., and Liu, L.
117. Seismicity of the Lau Basin as Viewed from Ocean-Bottom Seismometer and Sound Channel Moored Hydrophone Arrays. **Bohnenstiehl, D. R.**, Dziak, R. P., Conder, J., and Matsumoto, H.
118. Downhole Seismic Monitoring in the Istanbul/Eastern Sea of Marmara Region: Recent Results from the ICDP-GONAF Project. **Bohnhoff, M.**, Dresen, G., Bulut, F., Raub, C., Kilic, T., Kartal, R. F., Kadirioglu, F. T., Nurlu, M., Malin, P.E., and Ito, H.
119. An M 4.8 Earthquake in the Upper Mantle beneath the Wind River Range, Wyoming. **Pechmann, J. C.**, Koper, K. D., Herrmann, R. B., Whidden, K. M., Benz, H. M., Pankow, K. L., Lin, F., and Chapman, D. S.
120. Implications of Gravitational Anomalies within the Muckleshoot Basin of Northwest Washington. **Cox, J. H.**, Wolf, L. W., and Taylor, J. P.
121. Delineation Seismic Source Zones Based on Seismicity Parameters and Seismotectonic Characteristics around Sabah and North Borneo. **Adnan, A.**, Harith, N. S. H., and Shoushtari, A. V.

Friday, 02 May – Concurrent SSA Oral Sessions

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering Session Chairs: Luis A. Dalguer, Carlo Cauzzi, Aysegul Askan, and Philippe Gueguen (see page 508)	**Advances in Understanding Earthquake Hazard in Central and Eastern North America** Session Chairs: Robert Williams, Mitch Withers, William Stephenson, and John Ebel (see page 512)	**Seismic Location and Processing Techniques** (see page 516)	**A Decade of Great Subduction Earthquakes – What Have We Learned From Their Ground-Motions?** Session Chairs: Trevor Allen and Gail Atkinson (see page 520)	**Tracking Fluid Movement in Volcanic Systems** Session Chairs: John Lyons, Helena Buurman, Diana Roman, and David Fee (see page 524)
8:30 AM	INVITED: Does a 1D Velocity Structure Hurt or Help Ground Motion Predictions? **Crempien, J. G. F.** and Archuleta, R. J.	STUDENT: Paleoseismic Evidence for Persistent Intraplate Seismicity Associated with Reactivation of Precambrian Crustal Structures in Central Canada. Doughty, D., Eyles, N., **Wallace, K. E.**, Eyles, C. H., and Boyce, J. I.	Hypocentral Relocations Aided by Virtual Receivers Constructed via Seismic Interferometry. **Horowitz, F. G.**	INVITED: Ground-Motion Prediction Equations for Large Interface Earthquakes Based on Empirical Data from the 2011 M9.0 Tohoku, Earthquake. **Ghofrani, H. G.** and Atkinson, G. M.	Re-Examining the Tectonic/Magmatic Controls on Dynamic Triggering in the Brittle Crust. **Prejean, S. G.** and Hill, D. P.
8:45 AM	Stress Drop Variations and Their Relevance for Ground Motion Prediction. **Oth, A.** and Bindi, D.	The St. Lawrence Rift System and Its Relationships with Recent Earthquakes. **Lamontagne, M.**	Real-time Automatic Detectors of P and S Waves Using Singular Value Decomposition. **Kurzon, I.**, Vernon, F. L., Rosenberger, A., and Ben-Zion, Y.	INVITED: Magnitude Scaling Rates for Large Earthquakes in Ground Motion Prediction Equations for Japan. **Zhao, J. X.**	INVITED: Magmatic and Hytrothermal Fluid Controls on Deep, Distal and Shallow Volcanic Seismicity. **White, R. A.** and McCausland, W.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the EQ Source. . .	**Advances in Understanding. . .**	**Seismic Location. . .**	**A Decade of Great. . .**	**Tracking Fluid. . .**
9:00 AM	Stress Drop Variability and Its Relationship to Variability in GMPEs. **Baltay, A. S.** and Hanks, T. C.	USArray Transportable Array Evolving into the Central and Eastern United States Network (CEUSN). **Vernon, F.**, Busby, R., Woodward, R., and Astiz, L.	The Effects of Measurement Uncertainties on the Estimation of Seismic Gradients. **Poppeliers, C.** and Johnson, C. E.	INVITED: Broadband Synthetic Seismograms for M9 Cascadia Earthquakes Using 3D Simulations. **Frankel, A.**, Phillips-Alonge, K., Stephenson, W., and Delorey, A.	Do Pre-Eruptive Swarms have Systematically Different Earthquakes than Non-Eruptive Swarms? **Buurman, H.** and West, M. E.
9:15 AM	Identification of Near-Field Ground-Motion Characteristics and Predictors Based on Synthetic Data Obtained from Dynamic Rupture Models. **Dalguer, L. A.**, Cauzzi, C., Baumann, C., and Giardini, D.	STUDENT: Referenced Empirical Ground-Motion Model for Eastern North America, Based on the NGA-West 2 GMPE. **Hassani, B.** and Atkinson, G. M.	Doing More with Short Period Data: Using Coda Envelopes to Estimate Magnitudes for Clipped and Over-Run Earthquakes. **Wellik, J. J.**, McCausland, W., and Waite, G. P.	Broadband Strong Motion Simulations of Large Subduction Earthquakes. **Skarlatoudis, A. A.**, Somerville, P. G., Thio, H. K., and Bayless, J. R. B.	Short-Term Seismic Quiescence Immediately Preceding Explosive Eruptions. **Roman, D. C.**, Rodgers, M. J., Geirsson, H., LaFemina, P. C., Munoz, A., and Tenorio, V.
9:30 AM	Squeezing Kappa out of the Transportable Array: When the Going gets Tough. **Ktenidou, O. J.**, Silva, W., Darragh, B., Abrahamson, N. A., Kishida, T., and Cotton, F.	STUDENT: Comparing the CENA GMPEs using NGA-East Ground Motion Database. **Ogweno, L. P.** and Cramer, C. H.	Identification and Extraction of Surface Waves from 3-Component Seismograms Based on the "Normalized Inner Product". **Meza-Fajardo, K. C.**, Papageorgiou, A. S., and Semblat, J. F.	INVITED: NGA-Sub: Plan to Develop Next Generation Ground Motion Models for Subduction Earthquakes. **Bozorgnia, Y.** and Kishida, T.	INVITED: Evidence for Ongoing Magma Recharge at Mount St. Helens, Washington. **Moran, S. C.** and Lisowski, M.
9:45–10:45 AM	Break & Posters – Cook & Arteaga				

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering *(continued)*	**Advances in Understanding Earthquake Hazard in Central and Eastern North America** *(continued)*	**Recent Advances and Findings in Earthquake Geology and Paleoseismology** Session Chairs: Scott Bennett and Christopher DuRoss (see page 517)	**75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding** Session Chairs: Thessa Tormann, Max Wyss, and Jeanne Hardebeck (see page 521)	**Tracking Fluid Movement in Volcanic Systems** *(continued)*
10:45 AM	INVITED: Progress of the Southern California Earthquake Center Technical Activity Group on Ground Motion Simulation Validation. Luco, N. and **Rezaeian, S.**	Time Dependence of Magnitude Conversion Relations for Eastern Canada: More Complex than We Thought. **Bent, A. L.**	INVITED: Third Generation Paleoseismology: Clustering, Segmentation, Supercycles and Paleo Slip Models. **Goldfinger, C.** 30 minutes	INVITED: *b*-Values, Stress and Fault Heterogeneity during Laboratory Stick-Slip Experiments. **Goebel, T. H. W.**, Becker, T. W., Sammis, C. G., Schorlemmer, D., and Dresen, G.	STUDENT: Volcanic Tremor and Frequency Gliding during the 2011 Kamoamoa Eruption, Kilauea, Hawai'i. **Unglert, K.** and Jellinek, A. M.
11:00 AM	Stochastic Model for the Simulation of Seismic Ground Motion for Reliability Analysis of Industrial Structures and Components. **Zentner, I.**	STUDENT: Regional Study of Fourier Amplitude Drop of Lg-Wave Acceleration in Central United States. Chapman, M. C., Pezeshk, S., **Hosseini, M.**, and Conn, A.		INVITED: Growing Large Scale Fractures in a Salt Mine and Their Effects on the Frequency-Magnitude Distribution. Maghsoudi, S., **Cesca, S.**, Hainzl, S., Dahm, T., and Kaiser, D.	Air-Ground Coupling of Volcanic Tremor Using Cross-Spectral Analysis. **Fee, D. E.** and Matoza, R. S.
11:15 AM	Directivity Pulse Characterization of NGA-West2 Earthquakes – PSHA Implementation and Seismic Structural Response Implications. **Rowshandel, B.**	High-Resolution Aeromagnetic Data Illuminate Crustal Structure Associated with the New Madrid Seismic Zone, Missouri and Arkansas. **Blakely, R. J.**, Williams, R. A., Shah, A. K., Sherrod, B. L., and Weaver, C. S.	A 3D Marine Paleoseismology Investigation Offshore South Central Coastal California. **Nishenko, S. P.**, Greene, H. G., Hogan, P., and AbramsonWard, H.	INVITED: Geomechanical Modeling of Frequency-Magnitude Distributions of Induced Seismicity. **Bachmann, C. E.**, Wiemer, S., and Goertz-Allmann, B. P.	Seismic Radiation from Volcanic Conduits: Characterization of Propagating Waves and Source Excitation. **Karlstrom, L.** and Dunham, E. M.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the EQ Source. . .	**Advances in Understanding. . .**	**Recent Adv-Geology. . .**	**75 Years of. . .**	**Tracking Fluid. . .**
11:30 AM	Ground Motions Due to Earthquakes on Creeping Faults. **Harris, R. A.** and Abrahamson, N. A.	STUDENT: Relative Locations of Earthquakes and Potential Driving Mechanisms of Seismicity along the Northeast U.S. Atlantic Passive Margin. **Napoli, V. J.**, and Ebel, J. E.	10 m Slips on the Pitas Point Thrust: M8 Earthquakes in the Western Transverse Ranges of Southern California. **Rockwell, T. K.**, Clark, K., Oskin, M., Gamble, L., Haaker, G., Ucarkus, G., Kent, G., and Driscoll, N.	Tectonic b-Value Variation Interpreted as Stress-Meter – Examples from Different Scales. **Tormann, T.**, Wiemer, S., Woessner, J., and Enescu, B.	Volcanic and Non-Volcanic Events from the Nascent Mt. Pagan Seismo-Acoustic Network. **Lyons, J. J. L.**, Haney, M. M. H., Fee, D. E. F., Read, C. W. R., and Paskievitch, J. F. P.
11:45 AM	A Naive Bayesian Approach to Strong Ground Motionn Selection for Non-Linear Seismic Analysis of Structures. **Lancieri, M.**, Reanult, M., Lecomte, L., Perrault, M., Baumont, D., Gueguen, P., and Berge-Thierry, C.	Recent Earthquakes in the Central and Eastern U.S. Prompt Variable Responses to Reduce Future Earthquake Losses. **Williams, R. A.**	Multi-Method Measurement of Offset from the 1857 Fort Tejon Earthquake along the San Andreas Fault in the Carrizo Plain at Channel Sieh31. Akciz, S. O., **Grant Ludwig, L.**, Halford, D., Maliyani, G. I., Salisbury, J. B., Kleber, E. J., Arrowsmith, J. R., Rhodes, E., and Capaldi, T.	INVITED: Local Magnitude Distributions in the 3rd Uniform California Earthquake Rupture Forecast (UCERF3). **Page, M. T.**, Field, E. H., and Milner, K. R.	Cyclic Hybrid Swarms at Soufriere Hills Volcano, Montserrat, 1996–2001. **Thompson, G.** and McNutt, S. R.
Noon–1:15 PM			Lunch – La Perouse		

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering *(continued)*	**New Directions in PSHA: Ins, Outs, and Uncertainty** Session Chairs: Peter Powers, Morgan Moschetti, and Ned Field (see page 514)	**Recent Advances and Findings in Earthquake Geology and Paleoseismology** *(continued)*	**Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario – Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation** Session Chairs: Elena Suleimani, Stephanie Ross, Hong Kie Thio, and Dmitry Nicolsky (see page 522)	**Citizen Seismology: Citizens Helping Science Helping Citizens** Session Chairs: Paul Earle, Susan Hough, and Gail Atkinson (see page 526)
1:30 PM	On the Use of Earthquake Early Warning and Operational Earthquake Forecasting for Real-Time Risk Mitigation at Nuclear Power Plants in Switzerland. **Cauzzi, C.**, Behr, Y., Renault, P., Clinton, J., Wiemer, S., Le Guenan, T., Douglas, J., Woessner, J., Caprio, M., and Cua, G.	Incorporating Time Dependence in PSHA in the (Near) Absence of Data. **Biasi, G.**, Thompson, S., AbramsonWard, H., Abrahamson, N., Hanson, K., Lettis, W., Caskey, J., and Gregor, N.	STUDENT, INVITED: 3D Comparison of Coseismic Fold Deformation for the Last 5 Events across a Releasing Step-over at the Frazier Mountain Paleoseismic Site, Southern San Andreas Fault, CA. **Streig, A. R.**, Weldon, R. J., Scharer, K. M. 30 minutes	Far-Field Tsunami Detection and Warning, 1854–2014: One Hundred and Sixty Years in the Intricate Relation between Earthquake Source and Tsunami. **Okal, E. A.**	Earthquake Intensity Distributions: A New View. **Hough, S. E.**
1:45 PM	Real-time GPS enhanced Earthquake Early Warning: The Northern California Setup. **Grapenthin, R.**, Johanson, I. A., and Allen, R. M.	Computing Elastic-Rebound-Motivated Earthquake Probabilities in Un-segmented Fault Models – The UCERF3 Methodology Supported by Physics-based Simulators. **Field, E. H.**		Tsunami Modeling and Inundation Mapping in Southcentral Alaska. **Nicolsky, D. J.**, Suleimani, E. N., Koehler, R. D., and West, M. E.	Reconciling Intensity Prediction Equations with Ground Motion Prediction Equations. **Atkinson, G. M.**, Worden, C. B., and Wald, D. J.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the EQ Source. . .	**New Directions in PSHA. . .**	**Recent Adv-Geology. . .**	**50 Years of Tsunami. . .**	**Citizen Seismology. . .**
2:00 PM	An Evaluation of U.S. Geological Survey's PAGER's Alerting Accuracy. **Marano, K. D.**, Garcia, D., Hearne, M., Jaiswal, K., and Wald, D. J.	How Can We Combine Epidemic Type Aftershock Sequences (ETAS) and Finite Source Rupture Models? **Segou, M. S.**	A Tale of Two Seisms Down Under: 23 March 2012 Mw 5.4 Ernabella and 9 June 2013 Mw 5.6 Mulga Park. **Clark, D. J.**, McPherson, A., Allen, T.	Inundation Mapping and Hazard Assessment of Tectonic and Landslide Tsunamis in Southeast Alaska. **Suleimani, E.**, Nicolsky, D. J., and Koehler, R. D.	Quantitative Analyses of Did You Feel It? Data. **Worden, C. B.**, Wald, D. J., Quitoriano, V., and Caprio, M.
2:15 PM	Real-Time Shake Mapping in Istanbul. **Zulfikar, C.**, Tunc, S., Yas, T., and Erdik, M.	Probabilistic Seismic Hazard Analysis Using the Single Station Sigma Concept: Application to a New Nuclear Site. **Rodriguez-Marek, A.**, Rathje, E. M., Bommer, J. J., Scherbaum, F., and Stafford, P. J.	STUDENT: Geomorphic and Geologic Evidence of Recently Active Faults and Folds in Java, Indonesia. **Marliyani, G. I.**, Arrowsmith, J. R., and Helmi, H.	The SAFRR Tsunami Scenario: Improving Resilience for California from a Plausible M9.1 Earthquake near the Alaska Peninsula. **Ross, S. L.**, Jones, L. M., Wilson, R. I., Miller, K., Bahng, B., Barberopoulou, A., Borrero, J. C., Brosnan, D. M., Bwarie, J. T., Geist, E. L., Johnson, L. A., Kirby, S. H., Knight, W. R., Long, K., Lynett, P., Mortensen, C. E., Nicolsky, D. J., Oglesby, D. D., Perry, S. C., Plumlee, G. S., Porter, K. A., Real, C. R., Ryan, K., Suleimani, E., Thio, H. K., Titov, V. V., Wein, A., Whitmore, P. M., and Wood, N. J.	Performance of Several Low-Cost Accelerometers. **Evans, J. R.**, Allen, R. M., Chung, A. I., Cochran, E. S., Guy, R., Hellweg, M., and Lawrence, J. F.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the EQ Source. . .	**New Directions in PSHA. . .**	**Recent Adv-Geology. . .**	**50 Years of Tsunami. . .**	**Citizen Seismology. . .**
2:30 PM	Multi-Hazard Risk Maps for Coastal Communities of Washington. **Cakir, R.**, Walsh, T. J., Slaughter, S., and Norman, D. K.	INVITED: Using the Averaging-Based Factorization to Assess Low Frequency (<0.5 Hz) CyberShake Hazard Models. **Wang, F.**, Jordan, T. H., Callaghan, S., Graves, R. W., Olsen, K. B., and Maechling, P.	The Timing of the Recent Two Faulting Events on the Himalayan Frontal Fault in Ramnagar Area, Uttarakhand, India. **Okumura, K.**, Malik, J. N., Santiswarup, S., Naik, S. P., and Khan, A.	Advances in Tsunami Risk Assessment and Risk Mitigation. **Porter, K. A.**	Twitter Based Earthquake Detection and Characterization: System Assessment and Future Directions. **Earle, P. S.**, Guy, M. R., Horvath, S. R., Turner, J. S., and Bausch, D.
2:45–3:45 PM	Break & Posters – Cook & Arteaga				
Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering *(continued)*	**New Directions in PSHA: Ins, Outs, and Uncertainty** *(continued)*	**Recent Advances and Findings in Earthquake Geology and Paleoseismology** *(continued)*	**Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario – Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation** *(continued)*	**Earthquake Physics and Interaction** (see page 528)
3:45 PM	Fatalities in Greek Earthquakes, Past and Future. **Wyss, M.** and Tolis, S.	Visualizing the Range of Epistemic Uncertainty of GMPEs. **Kuehn, N. M.**, Gianniotis, N., Scherbaum, F., and Abrahamson, N.	New Paleoseismic Study of the Septentrional Fault, Dominican Republic. **Prentice, C. S.**, Scharer, K., Gold, R., DeLong, S., and Pena, L.	Numerical Modeling of the SAFRR Tsunami Scenario. **Thio, H. H.**, Suleimani, E., Ryan, K., Ross, S., Nicolsky, D., Knight, W., Lynett, P., Borrero, J., Wilson, R., and Geist, E.	STUDENT: Temporal and Spatial Clustering of Intermediate-Depth Earthquakes: Evidence for a Cascading Effect. **Barrett, S. A.** and Prieto, G. A.

Time	*Room 1*	*Room 2*	*Room 3*	*Room 4*	*Room 7/8*
	From the EQ Source. . .	**New Directions in PSHA. . .**	**Recent Adv-Geology. . .**	**50 Years of Tsunami. . .**	**Earthquake Physics. . .**
4:00 PM	Macroscale Vulnerability Assessment Using Association Rule Learning, A Data-Mining Tools. Riedel, I. and **Gueguen, P.**	INVITED: Comparison of Epistemic Uncertainty in Hazard in California between UCERF2 and UCERF3. **Shome, N.**, Powers, P. M., and Petersen, M. D.	Revised Earthquake Hazard of the Hat Creek Fault, Northern California: Paleoseismology in Pleistocene Lava Flows. **Kattenhorn, S. A.** and Blakeslee, M. W.	STUDENT: Modeling Megathrust Rupture through Stable-Sliding Zones, and Implications for an Alaskan-Aleutian Megathrust Earthquake and Tsunami. **Ryan, K. J.**, Oglesby, D. D., and Geist, E. L.	Time-Dependent Earthquake Forecasts on a Global Scale. **Rundle, J. B.**, Holliday, J. R., Turcotte, D. L., and Graves, W. R.
4:15 PM	Estimation of Seismic Losses in Urban Regions within an Interdisciplinary Framework: A Case Study. **Askan, A.**, Erberik, M. A., Yakut, A., Kilic, N., Karimzadeh, S., Sisman, F. N., and Asten, M.	INVITED: Testing for Ontological Errors in Probabilistic Seismic Hazard Models. **Jordan, T. H.** and Marzocchi, W.	A Candidate Fault Scarp from the 1872 Earthquake near Chelan, Washington. **Sherrod, B. L.**, Blakely, R. J., Barnett, E. A., Schermer, E., Lasher, J. P., Sherrod, J. M., Miller, B., and Slaughter, S.	Incorporating Progressive Rupture into Tsunami Models for Tsunami Warning. **Fryer, G. J.**, Becker, N. C., and Wang, D.	Seismic Evidence for Thermal Shear Runaway during Intermediate-Depth Earthquake Rupture. **Prieto, G. A.**
4:30 PM	Evaluation of Building Vulnerability Due to Liquefaction Using the Canterbury Earthquake Sequence Observations. **Ancheta, T. D.** and van Balleygooy, S.	Effects of Various Declustering and Smoothing Methods on Earthquake Catalogs and Consequences for Seismic Hazard and Seismic Risk in New Zealand. **Apel, E. V.** and Nyst, M.	INVITED: Challenges and Opportunities in Synthesizing Multiple Paleoseismic Data Sets. **Biasi, G. P.** and Weldon, R. J. 30 minutes	Joint Earthquake Source Inversion of Land- and Ocean-based Geophysical Sensors for Tsunami Early Warning. **Melgar, D.** and Bock, Y.	A Global Comparison of Crustal Earthquake Scaling from Stable Event Ratio Levels. Yoo, S. H., Walter, W. R., and **Mayeda, K.**
4:45 PM	Building Time-Dependent Earthquake Recurrence Models for Probabilistic Loss Computations. **Fitzenz, D. D.** and Nyst, M.	The Global Earthquake Activity Model: What It Is, What It Can Do, and How It Can Be Tested. **Jackson, D. D.**, Bird, G. P., Kagan, Y. Y., Kreemer, C., and Stein, R.		STUDENT: Meteotsunamis Generated by Mesoscale Convective Systems along the U.S. East Coast on June 13th, 2013. **Wertman, C. A.**, Yablonsky, R. M., Shen, Y., Merrill, J., Kincaid, C. R., and Pockalny, R. A.	STUDENT: Stress Drop Studies of Earthquakes in the Southern North Island and Cook Strait Region of New Zealand. **Barnes, K.**, Doser, D. I., and Abercrombie, R. E.

Friday, 02 May – Morning Poster Sessions

75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding
(see page 528)

1. A Lower Bound for Gutenberg-Richter's *b*-Value and Speculations on Fractal Dimensions. **Nava, F. A.**
2. Using b-values and Apparent Stress to Characterize Stability of Hydraulic Fracture Growth. **Karimi, S.**, Urbancic, T. I., and Baig, A. M.
3. Microseismicty and Glacier Dynamics at the Vaughn Lewis Icefall, Alaska. Lipovsky, B. P., **Karlstrom, L.**, and Denolle, M. A.
4. Evolution of the 2008 Mogul Earthquake Swarm, Reno, Nevada: Identifying Complex Structures in a Shallow Urban Seismic Sequence. **Ruhl, C. J.**, Smith, K., and Abercrombie, R. E.
5. How Complete is the ISC-GEM Global Earthquake Catalog? **Michael, A. J.**
6. Confidence Intervals for the Magnitude of the Largest Aftershock. **Shcherbakov, R.**
7. Statistical Properties of Aftershock Sequences Generated by Large Subduction Earthquakes. **Shcherbakov, R.**, Goda, K., and Atkinson, G.
8. The Temporal Stability of b-Value estimates and Its Implications for Regional and Local Studies. **Zúñiga, F. R.**, Figueroa-Soto, A., and Márquez, V. H.
9. 1/f and the Earthquake Problem: A Forecasting Framework Based on Fault Weakening and Scaling Constrained ETAS. **Yoder, M. R.** and Rundle, J. B.

A Decade of Great Subduction Earthquakes – What Have We Learned from Their Ground-Motions?
(see page 520)

10. Source Scaling Relations of Subduction Earthquakes for Strong Ground Motion and Tsunami Prediction. **Skarlatoudis, A. A.**, Somerville, P. G., Thio, H. K., and Bayless, J. R.
11. Ground-Motion Prediction Equations of Intermediate-Depth Earthquakes in the Hellenic Arc, Southern Aegean Subduction Area. **Skarlatoudis, A. A.**, Papazachos, C. B., Margaris, B. N., Ventouzi, C., Kalogeras, I., and EGELADOS Group.
12. Global Analysis of Rupture Duration for Intermediate and Deep Earthquakes. **Poli, P.** and Prieto, G. A.
13. Seismic High-frequency Radiation during the March 20th 2012 (Mw 7.5) Mexican Earthquake, Using Strong Motion Data. **Aguirre, J.**

Advances in Understanding Earthquake Hazard in Central and Eastern North America
(see page 512)

14. Ground Motion Site-Effects from Multi-Method Shear-Wave Velocity Characterization at Portable Seismograph Stations Deployed for Aftershocks of the August 2011 Mineral, Virginia Earthquake. **Stephenson, W. J.**, Odum, J. K., McNamara, D. E., and William, R. A.
15. Airborne Geophysical Survey Data Used to Infer Geological Features Associated with Fault Slip in the Central Virginia Seismic Zone. **Shah, A. K.**, Horton, J. W., McNamara, D. E., Spears, D. B., and Burton, W. C.
16. Earthquake Swarms Associated with the Saratoga-McGregor Fault System near Albany, NY. **Ebel, J. E.**, Jacobi, R. D., O'Hara, A., and Starr, J. C.
17. A New Set of Focal Mechanisms for the Eastern Tennessee Seismic Zone. **Cooley, M. T.** and Powell, C. A.
18. Hazard Associated with the Eastern Tennessee Seismic Zone. **Powell, C. A.**
19. Discerning Faults Responsible for the Charleston, South Carolina Earthquake of 1886. **Pratt, T. L.**, Shah, A. K., and Horton, J. W.
20. Lg Propagation and Attenuation across Continental Margins, Scotia Basin. **Mousavi, S. M.** and Cramer, C. H.
21. Initial ENA Empirical GMPEs Using the NGA-East Database. **Al Noman, M. N.** and Cramer, C. H.
22. Improving Stress Drop Measurements from EGF – Scaling and Stress Release in the Darfield-Christchurch, New Zealand Earthquake Sequence. **Abercrombie, R. E.**, Fry, B., Doser, D. I., and Gerstenberger, M.

Citizen Seismology: Citizens Helping Science Helping Citizens
(see page 526)

23. Detecting Frequency Content of Ground Motion with Smart Phones Using Wavelet Analysis. **Aktas, M.**, Kuyuk, H. S., Durgun, G. Y., and Dok, G.
24. Limits of Smart Phones as Seismic Sensors. **Kuyuk, H. S.** and Aktas, M.
25. Relationship between Seismic Intensities (MMI), PGA, and PGV for the April 20, 2013, Mw6.6 Lushan, China Earthquake and a Comparison with North America. **Mooney, W. D.** and Wang, H. L.
26. Developing Ground Motion Estimates from $M > 6.0$ Earthquake Intensity Observations for Use in ENA Emperical GMPEs. **Cramer, C. H.**
27. Frequency Distribution of JMA Seismic Intensity and Ishimoto-Iida Law. **Kato, M.**

Earthquake Physics and Interaction
(see page 528)

28. The Seismic Quiescence Phenomenon in Taiwan. **Wang, J. C.**, Shieh, C. F., and Wang, J. H.
29. The Construction of the Fault Model in Ordos, China. **Gao, B.**, wangql.box@263.net, Q., Jia, K., and Zhou, S.
30. Quantifying and Explaining the Frequency-Dependent Radiation Pattern of the 2000 Tottori, Japan, Earthquake. **Seats, K. J.** and Dunham, E. M.
31. Applying the Time-Domain Moment Tensor Inversion Technique to Regional Earthquake Data in the Puerto Rico-Virgin Island Region. **Martinez-Torres, F. A.**, and Lopez-Venegas, A.
32. A Fluid-Induced Seasonally Modulated Earthquake Swarm near Maupin, Oregon. **Braunmiller, J.**, Nabelek, J. L., and Trehu, A. M.

Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario – Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation
(see page 535)

33. California Marshes as Recorders of Paleotsunamis: Example from Pillar Point. Jaffe, B. E., Richmond, B. M., **Wilson, R.**, Hemphill-Haley, E., Kelsey, H. M., Peters, R., Leeper, R., and Watt, S.
34. Observations on the 1964 Distant-Source Tsunami Deposit at Crescent City, California, USA. **Hemphill-Haley, E.**, Kelsey, H., Graehl, N., Caldwell, D., Robinson, M., Loofbourrow, C., and Vermeer, J.
35. Geospatial Methods in Support of Tsunami Research. **Macpherson, A. E.**, Nicolsky, D. J., and Suleimani, E.
36. Tsunami Evacuation Modeling for Cannon Beach, Oregon. **Madin, I. P.**, Priest, G. R., and Watzig, R. J.
37. Seismic Monitoring Capabilities of the Caribbean and Adjacent Regions Tsunami Warning System. **von Hillebrandt-Andrade, C. G.**, Crespo Jones, H., Saurel, J. M., McNamara, D., Huérfano Moreno, V. A., and Working Group 1 UNESCO IOC Intergovernmental Coordination Group for the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE EWS)
38. Stochastic Models of Earthquake Slip for Probabilistic Tsunami Modeling. **LeVeque, R. J.**, Waagan, K., Gonzalez, F. I., and Lin, G.
39. A Coupled Model for Dynamic Wedge Failure, Coseismic Landslides, and Tsunami Propagation for Shallow Subduction Earthquakes. **Yao, Q.**, Hirakawa, E. T., Ma,

From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering
(see page 536)

40. 3D Spontaneous Dynamic Rupture on Geometrically Complex Faults: The 2010 Mw 7.1 Darfield (New Zealand) Earthquake. **Abolfathian, N.**, Galvez, P., and Dalguer, L. A.
41. Forecasting the Rupture Directivity of Large Earthquakes. **Donovan, J.** and Jordan, T. H.
42. Effects of Difference of Source Spectrum Modeling on Synthetic Motions in Empirical Green's Function Method. **Yamaguchi, M.**, Dan, K., and Kitamura, H.
43. Quantifying the Spatial Variability of Ground Motion Residuals Using Site-to-Site Closeness Index as a Distance Metric. Hollenback, J. C. and **Moss, R. E. S.**
44. Progress Report for the Center for Engineering Strong Motion Data in 2014. Haddadi, H., Stephens, C., Shakal, A., **Savage, W.**, Huang, M., and Parrish, J.
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Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships Among Seismic Rupture, Transient Slip, and Steady Creep

Oral Session · Wednesday · 8:30 AM · 30 April · Room 1
Session Chairs: Harmony V. Colella, Emily C. Roland and Aaron G. Wech

What do Seismic Imaging Constraints Really Tell Us about the Fault Zone in which Great Earthquakes and Slow Slip Operate?

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Several lines of evidence suggest that subduction zone thrusts lie within weak, possibly overpressured channels. Seismic reflection data often shows a relatively thin, high-reflectivity surface with occasional bright spots, indicative of rapidly varying impedance contrasts over length scales of tens of meters. Scattered coda of teleseismic P waves, such as in receiver functions, often show a thin low-velocity layer corresponding to the top of the subducting plate. These have been best documented in Cascadia, where a 2–4 km thick very low velocity channel is seen above a moderately slow subducting crust; similar structure has been seen in Alaska. The channels are characterized by elevated Vp/Vs ratios (>2.0), and extend both throughout the locked, seismogenic fault zone into the region of episodic tremor and slip. Commonly, this combination of low velocities and high Vp/Vs is taken to indicate high pore pressures, and hence a fault zone that can withstand only very low shear stresses. However, models of these signals indicate static porosities of 2–5% throughout a 2–4 km thick layer, extending to depths of 40 km, a situation that seems difficult to sustain. Highly elevated pore fluid pressure may not be a unique explanation for the seismic observations. At both the Alaska and Cascadia margins, the low seismic wavespeeds, high Poisson's ratios, and high anisotropies result in part from subduction of thick sediments. The presence of significant thickness of subducted and underplated sediment is consistent with observations of preserved subduction 'channels' in exhumed rocks. Although some elevation of pore pressure may be still needed to explain observations, if subduction of 2–4 km sediment is a significant factor in generating the seismic signatures, then the geophysical observations would reflect a much stronger thrust zone than one sustained by high pore pressure alone.

A Link Between Silica Enrichment and the Recurrence Time of Slow Earthquakes in Subduction Zone Forearcs

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Seismic and geodetic observations in subduction zone forearcs indicate that slow earthquakes, including episodic tremor and slip, recur at intervals of <6 to >24 months. In Cascadia, slow slip is segmented along strike and tremor data show a gradation from large, infrequent slip episodes to small, frequent slip events with increasing depth of the plate interface. Direct evidence of factors controlling the variability in recurrence times is elusive. We compile seismic data from subduction zone forearcs exhibiting recurring slow earthquakes and show that the average Vp/Vs of the overlying forearc crust ranges between 1.6 to 2.0 and is linearly related with the average recurrence time of slow earthquakes. In northern Cascadia, forearc Vp/Vs values decrease with increasing depth of the plate interface and with decreasing tremor-episode recurrence intervals. Low Vp/Vs values require significant addition of quartz in a dominantly mafic forearc environment. We propose that variable silica enrichment by 5–15% from slab-derived fluids and upward mineralization in quartz veins can explain the range of observed Vp/Vs values as well as the downdip decrease in Vp/Vs. The solubility of silica depends on temperature, and deposition prevails near the base of the forearc crust. We further propose that the strong temperature dependence of healing and permeability reduction in silica-rich fault gouge via dissolution-precipitation creep can explain the reduction in tremor recurrence time with progressive silica enrichment. Lower gouge permeability at higher temperature leads to faster overpressure development and low effective fault-normal stress, and therefore shorter recurrence times. Our results are also in line with numerical models of slip stabilization under dilatancy strengthening, and imply that temperature-dependent silica deposition, permeability reduction and overpressure development control dilatancy and thus slow earthquake behavior.

Laboratory Experiments of Seismic Cycles: Effects of Normal Stress and its Gradient

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We report our studies on laboratory experiments inspired by seismic cycles in subduction zones. We conducted friction experiments between a Plexiglass block and a Silicone Gel plate driven at a constant plate velocity [1]. By changing the normal force and the inclination angle of the upper block, we controlled the normal stress level and its gradient. As a result, we successfully observed a wide variety of slip events and size statistics [2]. In small normal force and small inclination angle conditions, slip events were dominated by slow events which occur uniformly at the block-plate interface, and the size statistics obeyed the power law with cutoff. In intermediate force and angle conditions, coexistence of small slow events in 'deep' (large normal stress) regions and giant events rupturing 'shallower' regions were clearly seen and the size distributions obeyed power-law with a peak at large sizes. In larger force and angle conditions, however, the giant slip events disappeared and only small and intermediate slip events were observed. Interestingly, when we did experiments at the boundary between the latter two regimes, very complex stick-slip cycles wandering about the latter 2 dynamics modes were seen.

Based on our visualization of 2D displacement fields at the frictional interface, we determined epicenter, rupture area, and the moment magnitude for each event, and we also estimated 2D stress distributions during stress accumulation processes. We found that rupture behavior for a giant event was significantly influenced by the stress distribution or stress history before the event.

Reference:

[1] T. Yamaguchi, M. Morishita, M. Doi, T. Hori, H. Sakaguchi, J. P. Ampuero, Gutenberg-Richter law in sliding friction of gels, J. Geophys. Res. Solid Earth, 116, B12306 (2011).
[2] T. Yamaguchi, T. Hori, H. Sakaguchi, J. P. Ampuero, to be submitted.

Scaling Relations and Along-Strike Segmentation of Episodic Slow Slip Events in Subduction Zones

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A wide spectrum of slow slip phenomena in subduction zones, ranging from low-frequency earthquakes to long-term slow slip events, demonstrates a linear relation between the equivalent event moment and duration; each property spanning 7 to 8 orders of magnitude. However, the linear relation is not clearly established for each type of phenomena, especially for episodic SSEs in individual subduction zones. Understanding their moment-duration relation is key to the study of SSE source physics and relation to megathrust earthquakes. In this study I set up a 3D planar Cascadia-like fault model, using gabbro rate-state friction data and near-lithostatic pore pressure at depths around the friction stability transition, to produce SSEs with spatiotemporal distributions similar to those observed in Cascadia. SSE source properties, including along-strike propagation distance, event duration, equivalent moment and stress drop, are quantified and their scaling relations are compared to the observation summarized by Gao et al. [BSSA, 2012]. Modeled SSEs have nearly constant stress drops of 0.001 to 0.01 MPa, due to the small effective normal stress

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around 1 MPa required in the SSE region. SSE moment scales approximately to the square of its duration, rather than following a generalized linear relation. This is due to the stress perturbation among multiple SSEs originated at different along-strike locations and their slip fronts approaching each other during propagation. The modeled scaling relations are independent of the individual SSE selection criteria using either the slip velocity at a particular depth or the moment rate in the SSE region. Synthetic surface displacement time series are also computed due to the slip evolution on the fault. Modeling results indicate that geodetically detected along-strike segmentation in Cascadia SSEs may result from slower fault slip velocities at these segmentation boundaries, which may cause displacement anomalies beneath GPS detection.

Similarity and Difference of Megathrust and Slow Tsunami Earthquakes: Interpretation from Observations and Simulation

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The large slip region of the 2011 M9.0 Tohoku megathrust earthquake was detected near the trench and seems to overlap with the south part of the 1896 Meiji Sanriku tsunami earthquake. To understand the nature of megathrust earthquakes, it is important to investigate the slip behavior in the shallow part of the plate interface. In this study, we applied a new inversion method (Yagi and Fukahata, GJI, 2011) and a hybrid back-projection (Yagi et al., EPSL, 2012) to tele-seismic data of the 2011 Tohoku earthquake, the 2006 Java tsunami earthquake and the 2010 Mentawai tsunami earthquake. We found a smooth slip near the trench, while pulse-like slip was detected in and around the hypocenter. In addition, we did not find the smooth and rapid slip event near the trench in the two slow tsunami earthquakes, as in the case of the 2011 Tohoku earthquake. The increasing slip-rate function near the trench for the two slow tsunami earthquakes is much gentle than that obtained in the case of the 2011 Tohoku earthquake.

Many previous studies pointed out that roughly all of the accumulated elastic strain in the seismic source region has been released by the 2011 Tohoku earthquake due to the dynamic frictional weakening (e.g. thermal fluid pressurization (TP)). In general, a lower static strength and initial stress near the trench than in the deeper part of the plate interface reflects the existence of weak clay minerals. Furthermore, because clay minerals tend to have low static permeability that promotes efficient TP, the TP mechanism is assumed to work at shallow depths near the trench.

To understand the difference and similarity of mega-thrust and slow tsunami earthquakes, we perform dynamic rupture simulations using simplified fault models and the mechanism of thermal fluid pressurization. We found that small fluctuations of initial shear stress near the trench, within 1 MPa, lead to differences in seismic moment release greater than two orders of magnitude.

Geodetic Estimates of Slow and Transient Slip in the Alaska Subduction Zone

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The Alaska subduction zone has displayed a range of slow and transient slip behavior. Over a ~300 km segment of the Alaska subduction zone near Anchorage and the Kenai Peninsula, we have observed two very large slow slip events (SSEs) on the plate interface, several likely or probable small slow slip events, and other transient changes in the width of the locked region on the megathrust interface. Two long and large slow slip events have occurred over roughly the same area in the Upper Cook Inlet region, essentially the region downdip of the 1964 rupture near Anchorage. Although the events cover roughly the same area, the time history of slip in the two events is different. The earlier event spanned ~2–3 years, while the later even spanned roughly four years. The slip in these two events accounts for ~20 years of cumulative plate motion, suggesting that this part of the interface slips entirely in slow events. To the southwest in Lower Cook Inlet, near Homer, multiple abrupt changes in the width of the locked region have occurred – possibly a series of slow events, but with a very different temporal character to the Upper Cook Inlet events. For the most part, outside of Cook Inlet the available data are too sparse to determine whether slow events occur or not. However, transient post-earthquake slip has been observed adjacent to an earthquake off Amchitka, and certain segments of the Alaska subduction zone have not seen any slow or transient events since the installation of the Plate Boundary Observatory.

Tectonic Tremor Locations throughout the Alaska-Aleutian Subduction Zone from 1999 to 2013

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Since its discovery in 2002, deep tremor has been observed in a variety of tectonic settings worldwide including the Alaska-Aleutian subduction zone. As is the case in other settings where observed, tremor signals along the Alaska-Aleutian subduction zone are difficult to study due to its low signal-to-noise ratio and long duration. One way investigators overcome these challenges is to characterize tremor by extracting repeating events (e.g. swarms of low-frequency earthquakes, very-low frequency earthquakes) from continuous seismic records and subsequently locate the origin of individual signals to understand the source. Using the running autocorrelation of continuous seismic recordings I am able to extract several repeating events within tectonic tremor throughout the arc as far east as Anchorage, AK and as far west as the International Date Line.Tremor remains an enigmatic phenomenon in that it occurs repeatedly in subduction zones downdip of where large earthquakes are known to rupture. Locations of repeating events within tremor along the Alaska-Aleutian subduction zone reveal a similar behavior especially in areas downdip of the 1964 M_w 9.2 Good Friday earthquake and the 1957 M_w 8.6 Andreanof Islands earthquake. In each area along strike where tremor is characterized, slip behavior in comparison to tremor locations is different. In some places such as the Shumagin Gap the plate interface is inferred to be freely sliding and the tremor is located around 45–60 km depth. In other areas like Kodiak Island, the plate boundary is locked and tremor locations occur between 40–50 km depth. Given the variety of slip behaviors along the arc in conjunction with tremor activity in each area, I hypothesize that tremor can occur in any subduction zone regardless of the degree of plate coupling. Depth errors range from $+/-$ 5 km to as much as $+/-$ 11 km depending the instrumentation in each area.

Examining Large and Small Earthquakes in the Costa Rica Subduction Zone to Probe Temporal and Spatial Megathrust Heterogeneity

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Along the Middle America subduction zone, the Cocos Plate subducts beneath the Caribbean Plate, producing a wide range of slip behaviors that have been observed with significant seismic and geodetic infrastructure. The range of slip observed covers typical earthquakes to slow slip events (SSE) and non-volcanic tremor (NVT). In addition to the range of slip observed, the subduction zone is host to a range of geologic features and processes that may also impact the slip behavior, including seamount subduction, tectonic erosion, and along-strike variations in plate origin and temperature. Understanding the links between the specific geologic features and characteristics of megathrust slip is critical, and the Nicoya Peninsula region of Costa Rica is an ideal place to examine these links given the wealth of observed slip and observation infrastructure. Here we focus on comparing source characteristics of both large and small earthquakes recorded on both teleseismic and local networks with geologic features that are present. In addition, we compare the seismic source characteristics with locations of previously determined SSE and NVT in the Nicoya Peninsula area. We determine source parameters, such as rupture duration, seismic moment, corner frequency, and apparent stress, using teleseismic modeling techniques for the large and moderate magnitude events, and using source spectra of the S-wave coda for the smallest events. The event catalog spans 1990 through the present, and includes comparisons for events before and after the 2012 Mw = 7.6 megathrust event near the Nicoya Peninsula. Preliminary results suggest apparent stress for aftershocks of the 2012 event fall between 0.1–10 MPa, although no strong spatial correlation exists between areas of high apparent stress and areas of high slip in the 2012 mainshock. In addition, we find larger apparent stress for earthquakes that occur in areas of seamount subduction as compared with areas of smoother Cocos Plate subduction.

Observations of SSE, Tremor, and Damaging Earthquakes on the Southern Hikurangi Margin, New Zealand

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The Hikurangi margin was the site of 3 large slow slip events (SSEs) during 2013. These included a recurrence of the deep (30–50 km depth) long-term Kapiti SSE that began in January 2013 and is currently (January 2014) ongoing. Moment release in this event is equivalent to an Mw7.0 earthquake. Previous Kapiti SSEs occurred in 2003 and 2008. The 2013 event activated non-volcanic tremor in at least two discrete regions around the SSE. We use a template matching filter to search continuous data from 2013 for arrival times later used to locate the events. We determine our range of templates by manually inspecting waveforms from high quality permanent stations located around the tremor patches. We use multiple template durations to increase the variability in our recovered tremor events. The relative time of the maximum value of the correlation coefficient between the template and the

continuous recordings are employed as ballistic arrival times to determine event locations with a non-linear location algorithm. With this approach, we have very little resolution of depth estimates for the tremor. However, if we assume the source is located on or near the plate interface, the events are occurring between about 20 and 35 km depth. Interestingly, one of the tremor patches lies up-dip of the SSE, near a region of crustal earthquake activation later in the SSE cycle that included a damaging M6.6 event.

The Downdip Location of ETS and Dehydration Fluids Channelled to Forearc Mantle Corner

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We first show that for Cascadia the zone of Episodic Tremor and Slip (ETS) is not a downdip continuation of the seismogenic zone. Based on our recently published reviews, ETS occurs ~50 km downdip of the seismogenic zone which is concluded to be thermally limited for this hot subduction zone. We then address the question of what does control the location of ETS. In another review we have shown that the location of ETS coincides remarkably well with the forearc mantle corner for the whole Cascadia margin. This association can be explained by a focusing in this corner of the fluids that are released from deep subducting oceanic crust with downdip increasing temperature and pressure. It has been inferred from seismic velocity data that the overlying forearc mantle in Cascadia is strongly serpentinized from these fluids, and laboratory data show that such serpentinite has very low permeability. Once sufficient impermeable serpentinite is formed, deep-dehydration fluids should flow updip in the permeable underlying subducting crust to the forearc mantle corner where they are released upward into the more permeable forearc crust. As well as the inference from the coincidence of ETS and the forearc mantle corner, indications of this concentrated fluid flux come from seismic tomography. Exceptionally low Vp/Vs is found in the forearc continental crust above the corner that suggests a concentration of silica; quartz is the only common mineral that has adequately low Vp/Vs and silica deposition is expected from the large integrated volume of rising fluids over the ~40 m.y. of the current subduction regime. The fluids should be silica saturated and silica solubility decreases rapidly upward with decreasing temperature and pressure. In several studies elsewhere, concentrated quartz vein arrays in deeply eroded sections have been explained by episodic silica deposition from the large integrated fluid flux above subducted plates.

Explosive Source Characterization

Oral Session · Wednesday · 2:15 PM · 30 April · Room 1
Session Chairs: Catherine Snelson, Christopher Bradley, Sean Ford and Kyle Jones

Hydrodynamic Modeling of the Near-Source Environment at a Jointed Site

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We perform near source hydrodynamic modeling of explosive events in granite for the Source Physics Experiment (SPE). The effort includes constitutive material behavior of the rock, the optimal means for representing the granite joint response, and the best modeling approach for including both the high-deformation source region and the complex material response in the near field. Each of these factors contributes to better estimates of explosion to seismic phenomena to help the verification community.

A newly developed material model, AZ-Frac, has been implemented in two separate hydrodynamic modeling codes. The continuum model includes: 1) visco-plasticity, 2) directional fracture, 3) initial and fracture related anisotropy, and 4) stochastic material heterogeneity. This model has been validated against observed acceleration data for both free field and surface measurements from SPE.

We also demonstrate the effects of joints. We know that compliant joints reduce both amplitudes and wavespeeds of shock. The scale effects of joints (both micro- and macro-scale) are modeled as 'smeared' joints. This is compared to explicit inclusion of macro scale joint sets.

Finally, by analysis of the coupling phenomena, we observe aspects of the source that require explicit modeling, to contrast some approaches that minimize modeling complexity through the use of simplification. Our models are performed using both the fully coupled Euler-Lagrangian modeling available in the Abaqus code and LANL developed hydrodynamic codes. This approach allows for explicit modeling of source characteristics in our model and cross validation between algorithms.

A New Fracture Material Model for Simulating Damage and Moment Tensor Descriptions of Simulated Explosion Sources for Source Physics Experiments (SPE)

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The damage mechanisms governing the behavior of geo-materials around an underground explosive source and near the free surface are key aspects to understanding how seismic waves are generated from such sources. Within the framework of hydrodynamic simulations of underground explosions, these damage mechanisms are described through appropriate material models. In an effort to improve the description of these damage sources, researchers at Los Alamos National Laboratory (LANL) have been working on the development and implementation of a novel continuum-based-viscoplastic strain-rate-dependent fracture material model, AZ_Frac. Some of the main features of this material model are its ability to describe continuum fracture processes, and at the same time, to properly handle pre-existing anisotropic material characteristics. The introduction of fractures within the material generates further anisotropic behavior that is also accounted for in the material model. LANL researchers have adjusted the material model to a granitic medium and have utilized it in a number of modeling efforts under the SPE project. In our modeling, we use a 2D, axisymmetric layered model of the SPE site consisting of a weathered layer on top of a half-space. To see whether the new fracture material model properly simulates the late-time material damage that can be resolved seismically, we couple the hydrodynamic simulation code with a seismic simulation code and propagate the signal to distances of up to 2 km. We then invert the signal for time-dependent moment tensors using a modified inversion scheme that accounts for multiple sources at different depths. We will present simulation and inversion results for SPE-1 (980 m/kt**1/3) and SPE-4′ (approximately 1700 m/kt**1/3).

Three Dimensional Simulation of Ground Motions Generated by Underground Explosions in Jointed Rock under Conditions of Uncertainty

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We have performed 3D high resolution simulations of underground explosions conducted recently in jointed rock outcrop as part of the Source Physics Experiment (SPE). The main goal is to understand the nature of the shear motions recorded in the near field under condition of uncertainties in a) the geological characterization of the joints, b) the spatial variability of the geomechanical material properties, and c) the spatial correlation of rock properties. The approach is stochastic. The joints are depicted using a Boolean stochastic representation conditional to observations and their probability density functions. Then, using a novel continuum approach, joints and faults are painted into the continuum host rock. Simulating wave propagation in discontinuous rock mass is highly non-linear problem and uncertainty propagation via intrusive methods is practically forbidden. Therefore, using nested Monte Carlo simulations, we have explored and propagated several uncertainty parameters. We have probabilistically shown that significant shear motions can be generated by sliding on the joints caused by spherical wave propagation. Polarity of the shear motion may change during unloading when the stress state may favor joint sliding on a different joint set. A sensitivity analysis of the response of the system to ranges of geomechanical input parameters has been conducted to evaluate the impact of the key geomechanical parameters on the generated ground motions. To understand the far field seismic signatures associated with near-field shear waves, we have abstracted the near field behavior into a probabilistic source-zone model that can be used in the far field wave propagation study.

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Implications for Chemical/Nuclear Equivalence from Observations and Hydrodynamic Calculations

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A chemical-to-nuclear conversion factor is used to adjust the chemical yield to an equivalent nuclear yield owing to putative differences in the coupling between chemical and nuclear explosions. Researchers in the explosion community do not universally accept or apply such conversion factors. A case in point is the Denny-Johnson 1991 study of scaling models involving large data sets of chemical and nuclear explosions in which no conversion factor was applied to the chemical yield. This fact has been used as justification for not applying a conversion factor when calculating predictions of seismic moment and corner frequency for Source Physics Experiments (SPE) tests using the Denny-Johnson model, while a conversion factor is applied for predictions based on other scaling models. In this paper, we present observations and predictions of the ratio $\Psi\infty/W$ where $\Psi\infty$ is the static level of the reduced displacement potential and W is yield for chemical and nuclear explosions. The results support the need for a yield conversion factor using the Denny-Johnson model. Furthermore, we carry out 1-D hydrodynamic calculations comparing 'effective' cavity and source (elastic) radii for nuclear and chemical explosions in order to investigate the implications for conversion factors, seismic moment, and corner frequencies for a granite medium.

Modeling r_{el} as the Nonlinear Inelastic-Elastic Transition near Explosion Source

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The 'equivalent-cavity,' or 'elastic' radius (denoted r_{el}) separating the near- and far-field zones is the critical parameter of all explosion source models. While being measured from the far-field seismic data, the principal use of r_{el} is in constraining the properties of the source. Conventional scaling laws for this radius developed from nuclear explosions do not always work for smaller and shallower chemical shots. Here, we investigate a physical definition of r_{el} as the radius of the inelastic-elastic transition, i.e., the proximity to the source at which nonlinear effects become dominant. Three groups of mechanisms contribute to such nonlinearity: 1) dynamic strengthening of the material and increasing toughness of fractures under fast loading; 2) rock failure, damage, fragmentation, and fracturing, and 3) interactions with the free surface and preexisting near-surface structures. The first two of these groups can be described by the concept of effective medium with generalized, nonlinear viscoelastic rheology. Previous attempts for modeling such rheologies focused on constructing a strain-dependent quality factor (Q) for the medium. However, it is difficult to constrain or assume a meaningful frequency-dependent Q at near-source conditions. We propose a much broader, equivalent-medium approach using the concepts of nonlinear damage rheology and solid viscosity. These concepts are compatible with continuum mechanics, and thermodynamics, and they lead to straightforward finite-difference (FD) schemes. The waveforms and spectra of the resulting seismograms and the effective frequency-dependent Qs of the medium are explained by the dependences of elasticity and viscosity on strains and strain rates and by contributions of internal variables, such as temperature and the degree of damage. The model is illustrated by FD simulations of a radially-symmetric chemical source in an isotropic medium.

Relocation, Discrimination, Magnitude Calculation and Yield Estimation of the 12 February 2013 North Korean Nuclear Test

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On February 12, 2013, North Korea conducted its third and the largest nuclear test to date in the China-North Korea border area. Due to its large magnitude, the seismic records from this event have better signal-to-noise ratios than those from two previous nuclear explosions (hereafter, these explosions are referred as NKT1, 2 and 3). We use regional waveforms recorded on China National Digital Seismic Network (CNDSN), Global Seismic Network (GSN), and Japan F-NET to investigate the NKT3 for its location, event discrimination, and yield estimation. Using 100 Pn arrival data and the relative location method, we obtain the location for NKT3 to be [41.2923±0.0004° N, 129.0727±0.0006° E], approximately 3.0 and 0.4 km away from the NKT1 and NKT2, respectively. The relocation precision is approximately 52 m. For the North Korean nuclear explosions and a group of nearby earthquakes, we calculate Fourier spectral ratios Pg/Lg, Pn/Lg, and Pn/Sn from vertical-displacement waveforms on stations with pure continental paths. After distance corrections and eliminating the data with signal-to-noise ratios below 1.8, these ratios can fully discriminate the explosion and earthquake populations at frequencies above 2.0 Hz, indicating an explosion within this magnitude range detonated in China-North Korea border area can be determined by a regional network without ambiguity. After calibrating the network with a Lg-wave dataset (685 broadband waveforms from 98 regional events between December 1995 and February 2013) and a broadband Lg-wave attenuation model, we obtain the Lg-wave magnitude mb(Lg)=4.91±0.22 for NKT3. By further using a fully coupled hard-rock site model, the yield for NKT3 is estimated to be 7.47 kt based on it is detonated at the scaled depth. However, if it is strongly over buried, this yield may be underestimated.

Seismic Analysis of the North Korean Nuclear Explosion on February 12, 2013

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On February 12, 2013, North Korea conducted an underground nuclear test in the north-eastern mountainous granite rock of the country. The test was located by USGS at 41.308 N and 129.096 E and its yield was estimated to be 12 kt. The Lg magnitude mb(Lg) was 4.9 (5.1 USGS), the explosion being stronger than that in 2009 with mb(Lg) of 4.5 (4.5 USGS) or in 2006 with mb(Lg) of 3.9 (4.2 USGS). Since the radiated seismic waves were recorded at most of stations over the world, the explosion became one of the best ever recorded nuclear explosions in history, suitable to be exploited in various structural and source studies. Here we focus on determining source parameters of the explosion, the seismic moment tensor and the source-time function in order to study detailed physical and tectonic conditions at the source and to verify an explosive character of the source. We show that the explosion displays partly non-isotropic radiation which has been reported also for the 2009 nuclear explosion, and we discuss its possible physical origin.

Ms Unified: A New Magnitude for Rayleigh and Love Waves with Application in the Korean Peninsula and Yellow Sea Region

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In order to improve discrimination of small explosions and earthquakes, we need to change the focus of magnitude estimation from large scale network sampling to maximizing the available information from single stations and then combining into network estimates, designed to be effective with sparse network coverage.

We have developed a new magnitude scale, based on the Ms(VMAX) technique of Russell (2006), that incorporates both Love and Rayleigh wave amplitudes for a unified surface wave magnitude. The Love and Rayleigh waves are narrow band filtered and corrected for propagation and source effects at periods between 8–25 seconds, in order to find filter bands of maximum energy propagation. The unified magnitudes (termed MsU) are calculated from average amplitudes of both Rayleigh and Love waves at each station, measured at each period, and then scaled to standard 20 sec Rayleigh magnitudes. This is essential to minimize the effect of earthquake radiation patterns for sparse networks. The data are also corrected for censoring effects at the station level given that either Rayleigh or Love waves may not be observed for an event. We have applied MsU to 39 earthquakes ($3.21 < Mw < 5.08$) located in the Korean Peninsula and Yellow Sea region as recorded at near-regional distances (50–600 km). For comparison, we also estimated magnitudes based only on Rayleigh (MsR) and Love (MsL) waves. The MsU estimate consistently falls between the MsR and MsL estimates, with a significant reduction in outliers. The standard deviations of residuals for the different magnitudes are 0.15 (MsU), 0.19 (MsR), and 0.23 (MsL), with significantly improved stability of the MsU residuals as a function of distance. The reduction in variance for MsU will provide a magnitude that is a better indicator of source size for single-station and sparse network estimates, which has important implications in discriminating earthquakes and explosions at small magnitudes.

Identifying and Characterizing Blasts from Recordings at USArray Stations

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As the traverse of EarthScope USArray stations draws to an end, the Array Network Facility (ANF) has located nearly 80,000 seismic events in the continental U.S. since April 2004. The ANF seismic bulletin is complete to MR $\sim$ 2.1 but does not distinguish between earthquakes and blasts. In contrast to regional seismic catalogs in the U.S. that mostly report naturally occurring seismicity with varying magnitude thresholds. Thus it is not surprising that only half of the events reported by ANF are associated with those reported by the regional networks. Considering only local time of occurrence of events in the ANF bulletin, we conclude that mining blasts may

comprise up to a third of the events reported. So the ANF bulletin contains a wealth of data that can help characterize mining blasts. Ideally, mine blasts can be identify by getting ground truth information from mining operation, or by associating event origins with origins in the U.S.G.S. mining catalog but only a small portion of events can be identified in this manner. By cross correlating waveforms of events occurring within 10 km of active mines at USArray stations located within 300 km to these events, we are able to group events with similar characteristics. Then, once events have been identified as probable blasts, we will analyze if waveform characteristics in the frequency domain both from blasts of surface or underground mines as compared to tectonic events by analyzing the frequency content of waveforms at stations at similar ranges.

Improving Yield Estimation For Near-Surface Explosions Using Seismic And Overpressure Data

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We have developed a methodology to estimate the yield of near-surface explosions using a joint analysis of seismic ground motion and atmospheric overpressure. Because of the partitioning of energy into the ground and air for explosions near the Earth's surface, best results are obtained from combined analysis of seismic and overpressure data solving for both yield (W) and emplacement height-of-burst or depth-of-burial (HOB/DOB). Amplitudes of seismic P-waves and air-blast positive phase impulse are measured and used in grid search and Markov Chain Monte Carlo (MCMC, stochastic) inversions. The MCMC method allows us to propagate measurement and model errors without the need to assume underlying statistical distributions and has other advantages for this problem. We have applied this method to data from recent chemical high-explosive experiments and historical nuclear tests. The method has been successful for estimating W with errors of less than 50% and often inferring the correct sign of the emplacement (above or below ground). However, there are notable areas for improvement, particularly the empirical models for the seismic amplitude dependence on W, HOB/DOB and range. We show that the emplacement lithology (material strength) has a strong impact on seismic amplitudes. We report differences between seismic signal amplitudes for dry alluvium and hard rock, including W and HOB/DOB effects. We used recently digitized historical waveform data from chemical and nuclear explosions and will report differences in seismic and air-blast excitation from these source types.

Geometric Complexities Along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution

Oral Session · Wednesday · 8:30 AM · 30 April · Room 2
Session Chairs: Sean P. Bemis, Jeff Benowitz and Michele Cooke

Dynamic Models of the 2010 Sierra El Mayor-Cucapah Earthquake

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The M 7.2 2010 Sierra El Mayor-Cucapah Earthquake took place on a complex system of oblique normal/right-lateral faults separated by apparent stepovers and gaps as large as 5 km wide and 11 km long. The primary rupture propagation was from the Southeast to the Northwest, but an eyewitness account describes a reversed rupture propagation along at least one portion of the surface fault trace. We use the 3D dynamic finite element method and fault geometry motivated by both LIDAR and InSAR imagery to investigate the physical causes of the complex rupture behavior in this event. We find that for rupture to jump the largest stepover (in the Accommodation Zone between the two largest fault segments), some sort of previously-unmapped slip structure(s) must exist in the intervening space, either at depth or intersecting the surface. Backwards rupture propagation may be explained simply by the behavior of rupture after jumping a stepover, at which point it tends to propagate bilaterally. The ground motion from this geometrically complex fault system is also quite complex, with a bias toward higher ground motion on the hanging wall sides of the dipping fault segments. The results help to explain not just the physics of this event, but to foreshadow the behavior of suites of small fault segments in potential complex earthquakes in the future.

Stress Drop Heterogeneity within Complex Tectonic Regions: A Case Study of the San Gorgonio Pass, Southern California

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Slip along tectonic faults during earthquakes generally leads to a reduction in average shear-stress within the source region. The amount of stress decrease may vary, e.g., as function of fault geometry, depth, crustal thickness and faulting type. Here, we test a range of crustal parameters to advance our understanding of underlying mechanisms of spatial stress-drop variations. We analyze source spectra of small and intermediate magnitude seismic events within the San Gorgonio pass region. This region marks the location of a restraining bend within the San Andreas fault system resulting in complex, distributed deformation along systems of strike-slip and thrust faults. Stress drops are computed by fitting a Brune-type spectral model to individual event source spectra. These spectra are determined by iteratively stacking the observed amplitude spectra and correcting high frequency contributions by using a regional empirical Green's function. The results are subjected to a sensitivity analysis of input parameters to verify their stability. Stress drops show strong spatial variations ranging from 0.1 to 100 MPa with a median of about 5 MPa. Stress drops are higher for thrust events (about 8 MPa) whereas normal faulting events exhibit lower values of about 3 MPa. We observe an abrupt increase of stress-drops with depth at about 10 km. In addition, stress drops of events along the San Andreas fault correlate with geologic slip rates so that relatively low slip rates are associated with high stress-drops and vice versa. The spatial variations in stress-drops are likely sensitive to both crustal conditions and fault properties and can thus advance the assessment of regional differences in earthquake ground motions.

Comparison of Fault Behavior across the Big Bend of the San Andreas Fault, California

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The 'Big Bend' of the San Andreas Fault (SAF) is a large restraining bend with localized areas of differing geometric and seismologic complexity. For example, compared to the dearth of seismicity along the simple, linear portions of the fault, the southern Big Bend in the San Gorgonio Pass Region is characterized by higher rates of recent seismicity and complex fault networks. In contrast, at the northern end of the Big Bend (where the Garlock Fault impinges) the SAF remains a single, strike-slip strand with low seismicity rates despite a relatively tight bend. We review paleoseismic event data from both ends of the Big Bend and place these results within the context of published regional geophysical studies and slip rates. At the Frazier Mountain paleoseismic site, the last ~600 years of large earthquakes shows remarkable consistency with the Carrizo section, yet differs from sites to the south on the Mojave section. Geologic slip rates taper somewhat along this 200 km span (geodetic rates vary), but geophysical studies indicate the fault transitions from a moderate SW dip to vertical just SE of the northern Big Bend, hinting that geometric changes could control earthquake behavior at smaller timescales but are not important at longer timescales. This pattern does not appear to hold in the San Gorgonio Pass region, which hosts dramatic changes in the fault orientation and complexity, high surface uplift rates (>2 mm/yr), and a marked drop in the horizontal slip rate. Here, the paleoseismic rates also change; the interval between ground-rupturing earthquakes at the Cabazon paleoseismic site is >7 times longer than on the linear strands of the fault outside of the Pass, suggesting that ruptures are rare and/or quite distributed through the Pass. Thus, greater fault complexity in the south versus greater continuity in the north appear to correlate with the scale of differences in short-term earthquake rates and the longer-term SAF behavior.

Rates and Patterns of Vertical Deformation Along the Northern San Andreas Fault

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Relative horizontal motion along strike-slip faults can build mountains when motion is oblique to the strike-slip boundary. The resulting contraction and uplift pose seismic hazards, but are often difficult to detect because of the poor vertical resolution of satellite geodesy and difficulty of locating offset dateable

landforms in active mountain ranges. We present new constraints on mountain growth and erosion along the northern San Andreas Fault (SAF) and compare these with existing studies. Marine terraces indicate that late-Pleistocene uplift rates west of the SAF near Point Arena, CA, are between 0.2 and 0.45 mm a^{-1}. A narrow region of uplift with rates between 0.6 and 1.0 mm a^{-1} is expressed east of the fault but uplift decays east and north along the coast and away from the SAF. U-Pb dating of tuff in the shallow marine Ohlson Ranch Formation indicates deposition ca 4.5 Ma. This now sits at 400 masl adjacent to the SAF, but warps down to 150 masl 15 km east of the SAF, and is exposed at 60–110 m in translated outcrops west of the SAF. Catchment-mean erosion rates derived from cosmogenic ^{10}Be concentrations in river sediment east of, and adjacent to, the SAF are 0.14 to 0.35 mm a^{-1} but are only 0.03–0.07 mm a^{-1} west of the SAF. Channel steepness index is highest adjacent to the SAF and in the upper parts of drainage basins where drainage divides are migrating eastward. These data indicate that the SAF is a boundary between differing vertical tectonic regimes, and rock uplift may be accommodated by vertical motion along the SAF or closely associated structures. The patterns of uplift indicate that mountain building in the region is recent, is not balanced by erosion is highest just east of the SAF and has accelerated since the early Pliocene. Together, this suggests off-fault seismic hazard may be particularly high in a zone of uplift and shortening within a few kilometers of the fault zone.

Did Someone Forget to Pay the Earthquake Bill?

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Paleo-seismic data for California imply a long term rate corresponding to a recurrence interval of decades, yet the rate during the instrumental seismic measurement era is considerably less. The third Uniform California Earthquake Recurrence Forecast (UCERF3) project bases estimated future earthquake rates largely on dates of observed paleo-seismic displacements at 31 sites on 13 named faults in California. The summed event rates for the whole ensemble of sites is about 0.1 per year. Allowing generously for occurrences of earthquakes that rupture multiple sites simultaneously, the event rate is on the order of 0.04 per year. Yet the most recent event date is 1910. Such a long open interval would be extremely unlikely for a Poisson process with that rate, which might be expected statewide even if individual faults ruptured in quasi-period events. Quasi-periodic behavior for the whole ensemble would make the discrepancy worse. Has some un-modeled force put tectonic processes into hibernation? If so, what is it, and how long can the Bear State sleep? Or is the relationship between paleo-seismic displacements and earthquakes not as close as assumed? What do you miss when you focus only on individual faults, rather than the ensemble?

Basement Structure and Earthquake Hazards along the Queen Charlotte-Fairweather Fault System, Southeastern Alaska

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In southeastern Alaska, neotectonics are dominated by the Queen Charlotte-Fairweather dextral transform fault system, which accommodates motion between the Pacific and North American plates. The slip rate is around 4.5 cm/yr, with a vector of oblique convergence increasing southward up to 20 mm/yr. The Queen Charlotte Fault (QCF), bounded by the complex Explorer triple junction to the south and the Yakutat triple junction to the north, has caused several large (> Mw 7) earthquake events, and many questions still remain about the QCF's surficial geometry, regional stresses, tectonics, and fault plane structure. Study of the QCF to this point has been confined to localized regions; we use a compilation of marine geophysical data along the fault trace to provide unique insight into the big-picture changes in fault geometry, structure, and plate dynamics.

Two recent earthquakes – a Mw 7.8 oblique-thrust event on 28 October 2012 offshore of Haida Gwaii and a Mw 7.5 strike-slip event near Craig, AK on 05 January 2013 – emphasize the importance of understanding fault structure along this active margin, especially in the context of other historical events. Models for accommodation of oblique convergence along the southern QCF are debated, suggesting Pacific Plate underthrusting, distributed intraplate deformation, or some combination of the two. Using a compilation of USGS and academic seismic reflection surveys and GLORIA sidescan sonar data, we re-map the QCF trace and constrain its surficial geometry and splays. We also map basement structure throughout the region and note downward flexure of the Pacific Plate on the northern edge of Haida Gwaii, shallowing southward to the Explorer triple junction. Normal faults in the sediment atop the Pacific Plate in the flexure region suggest an element of extension, perhaps caused by flexure and/or transtension from a right-stepping right-lateral fault system.

Implications of Recent Large Earthquakes on the Queen Charlotte Fault

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The Queen Charlotte Fault (QCF) accommodates predominantly right-lateral strike-slip motion between the Pacific and North American plates from the Explorer plate to the Fairweather Fault. The largest recorded earthquake along this boundary is the August 22, 1949 (Ms< 8.1) right-lateral strike-slip event. Southeastward from the 1949 rupture the QCF locates offshore of Haida Gwaii with a modest restraining bend resulting in compression and uplift of the Wrangelia terrane. The current obliquity of the relative plate motion is less than 20° from boundary parallel, prompting contention over the existence and extent of any underthrusting and associated seismic hazard. The October 28, 2012 (Mw 7.8) Haida Gwaii thrust earthquake ruptured offshore of Moresby Island, producing a substantial local tsunami and confirming the existence of strong slip partitioning into separate fault systems. Lay et al. (EPSL, 2013) modeled seismic and tsunami observations, finding an average slip of 3.3 m on a shallow-dipping plane below an offshore sedimentary terrace seaward of the QCF. Modeling of coseismic GPS deformation (Nykolaishen et al., AGU, 2013) and minor coastal submergence observed along Moresby Island (Haeussler et al., AGU, 2013) confirm the offshore slip. Lacking historical documentation of rupture of the QCF along this part of the margin, the potential for strike-slip failure of the QCF along Moresby Island remains unclear. With pre-event GPS observations in Haida Gwaii indicating plate-motion parallel deformations, there is significant boundary parallel shear stress that needs to be accounted for that was not released seismically in the 2012 event, nor in its afterslip. It is difficult to attribute this to shear-stress on the QCF, and more plausibly can be explained by viscous coupling of the deeper underthrust flange of Pacific plate in direct contact with North America beneath the islands. This implies low potential for large strike-slip faulting on this stretch of the QCF.

Rupture Behavior on Two Parallel Strike-Slip Faults: A Case from the Central Longriba Fault Zone, Eastern Tibet

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Fault behavior on two parallel faults is worth studying for seismic hazard assessment because it is always related to a large earthquake. The 2008 Wenchuan earthquake that ruptured two faults on the Longmen Shan fault zone provides a case for co-rupture on two parallel thrust faults. Whether two parallel strike-slip faults can rupture simultaneously in a large earthquake remains unknown. The central Longriba fault zone, ~200 km northwest of and parallel to the Longmen Shan in eastern Tibet, is composed of two subparallel strands: Longriqu fault in the west and Maoergai fault in the east 20–30 km apart. Displaced landforms indicate that these two strands are dominantly right-lateral strike-slip faults in Late Quaternary. We conducted trenching combined with radiocarbon and Optically Stimulated Luminescence (OSL) dating to reconstruct paleoseismic history. Our results demonstrate that four surface-rupturing events occurred on the Longriqu fault at 5080 ± 90, 11,100 ± 380, 13,000 ± 260, and 17,830 ± 530 cal yr B.P. and three events on the Maoergai fault at 8510 ± 420, 7100 ± 70, and 5170 ± 80 cal yr B.P. If only a single fault is considered, each fault strand fits a cluster model with a moment magnitude (Mw) of ~7.2–7.4. If we consider these two fault strands as a whole, the last event has a good temporal correlation that implies a co-rupturing event equivalent to Mw ~7.6. Prior to the last event, the two strands have an alternative activity, and the central Longriba fault zone appears to undergo a regular recurrence with an interval of ~2000 years. These results suggest that these two fault strands probably ruptured simultaneously in the last larger event and may merge at the seismogenic depth, in accordance with available deep seismic data. This study suggests that two parallel faults linked at the seismogenic depth may rupture together and generate a superquake.

Modeling Observed Aftershock Sequences with an Earthquake Simulator

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Due to the complex nature of faulting in southern California, knowledge of rupture behavior near fault step-overs is of critical importance to properly quantify and mitigate seismic hazards. Early dynamic models and earthquake simulators only incorporated vertical faults with highly simplified geometries. Many current studies examine the effects of varied fault geometry, fault step-overs, and fault bends on rupture patterns; however, these works are limited by the small numbers of integrated fault segments and simplified orientations. The previous work of Kroll et al., 2013 on the northern extent of the 2010 El Mayor-Cucapah rupture in the Yuha Desert region uses precise aftershock relocations to show an area of complex

conjugate faulting within the step-over region between the Elsinore and Laguna Salada faults. Here, we employ an innovative approach of incorporating this fine-scale fault structure defined through seismological, geologic and geodetic means in the physics-based earthquake simulator, RSQSim, to explore the effects of fine-scale structures on stress transfer, rupture propagation, and aftershocks. The simulations incorporate the fine-scale complex secondary faults in the Yuha Desert area into a large-scale model of the major faults in state of California and northern Baja California. Comparisons between the observed and predicted aftershock patterns in the Yuha Desert step-over allow for investigation of processes controlling aftershocks in regions with complex faulting. Recent simulation results compare favorably with the observed seismicity. Simulations most notably produce secondary aftershock sequences that increase the rate of aftershock decay, which are similar to the observations. We further investigate how the spatial and temporal distribution of aftershocks are affected by changes to model parameters such as shear and normal stress, rate-and-state frictional properties, fault geometry, and slip rate.

Strike-Slip Fault Segment Propagation and Linkage Via Work Minimization

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Over multiple earthquake cycles, strike-slip faults link to form through-going structures, as demonstrated by the continuous nature of the mature San Andreas fault system in California relative to the younger and more segmented San Jacinto fault system nearby. Despite its immaturity, the San Jacinto system accommodates between one third and one half of the slip rate along the boundary between the North American and Pacific plates. Better understanding of how the San Jacinto system has evolved over geologic time and of current interactions between faults within the system is critical to assessing this seismic hazard accurately. Numerical models of fault system development are challenged by the multiple physical mechanisms involved. For example, laboratory experiments on brittle materials show that faults propagate and eventually join (hard-linkage) by both opening-mode and shear failure. In addition, faults interact prior to linkage through stress transfer (soft-linkage). The algorithm GROW (GRowth by Optimization of Work) accounts for this complex array of behaviors by taking a global approach to fault propagation. In GROW, faults evolve to minimize the work (or energy) expended during deformation, thereby maximizing the mechanical efficiency of the entire system. GROW models with idealized pairs of faults reveal that the initial fault spacing and the applied stress orientation control fault linkage propensity and linkage patterns.These models allow the gains in efficiency provided by both hard-linkage and soft-linkage to be quantified and compared. Alongside the increasing mechanical efficiency associated with fault propagation and linkage is an increasing likelihood for single, larger earthquakes that rupture multiple fault segments. These models reinforce the sensitivity of fault segment linkage to both fault structure and the regional tectonic stress orientation controlled by plate motions.

Deciphering the Earthquake and Tsunami History of Subduction Zones

Oral Session · Wednesday · 1:15 PM · 30 April · Room 2
Session Chairs: Marco Cisternas, Lisa Ely, Ed Garrett, Daniel Melnick, Alan Nelson and Robert Wesson

The 1730 and 1751 Chilean Earthquakes: Two Major Contributors to the Seismically Prolific 18th Century along the Pacific Coast of the Americas

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Large underthrusting earthquakes along the Pacific coast of the Americas seem to have clustered during the first half of the 18th century. Fault ruptures that reportedly generated large tsunamis occurred in the northwestern United States in 1700, in south-central Mexico in 1732 and 1754, in central Peru in 1746 and in central and south-central Chile in 1730 and 1751. The latter two events damaged towns along 800 km and initiated destructive tsunamis that crossed the Pacific to Japan. Although these two Chilean earthquakes were only 21 years apart, there was significant overlap in the areas that sustained damages from each event.

We studied the 1730 and 1751 earthquakes and tsunamis through their geological and historical records. We searched for primary historical sources in the archives of Spain, Peru, Argentina and Chile. We also scrutinized first-hand Japanese reports of the effects of both tsunamis on the eastern coast of Honshu. At two Chilean coastal sites, Campiche (32.7° S) and Tirúa (38.3° S), we described and dated sand sheets that were probably deposited by these tsunamis. Finally, we compared the effects of these historical events with those of two other modern and better-known ones: the Mw 9.5 1960 and the Mw 8.8 2010 earthquakes.

Our results indicate that the effects of both the 1730 and 1751 events were greater than those of 2010 and less than those of 1960. If they were in fact larger than Mw 8.8, it would imply that the release of accumulated slip and seismic moment during the first half of the 1700s was exceptionally large along the Chilean coast, adding to the potential significance of this seismic period along the entire coast of the Americas.

A Comparison of Tsunami Deposits from the 1960 Great Chilean Earthquake in Two Coastal Lakes on Chiloé, Chile

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On the 22nd of May, 1960, the Valdivia segment of the Peru-Chile megathrust ruptured in the strongest earthquake (EQ) ever instrumentally recorded (MW 9.5). This EQ produced a tsunami which struck approx. 1000 km of the near-field coast of South-Central Chile. The Island of Chiloé is located in the middle of the Valdivia segment and its west coast was inundated by 3 to 4 strong waves with a maximum wave height of approximately 15 m (Sievers et al., 1963). For two coastal lakes on Chiloé, namely Lago Cucao and Lago Huelde, the land barrier between the ocean and the lakes with 1.2 km width and 5–6 m elevation did not prevent the tsunami from inundating them. The lakes are only 2 km apart, lie behind the same beach and their outlets meet before flowing into the ocean. This setting gives a unique opportunity to compare the influence of onshore topography and lake bathymetry on inundation characteristics and on how the event is archived in the geological record. Side scan sonar data and pinger sub-bottom profiles were obtained and 36 gravity cores were analysed for geophysical properties, grain size and by x-ray computer tomography. In both lakes the cores contain 1960 tsunami deposits in form of sandy to silty beds, often with mud rip-up clasts. These deposits stand out in contrast to the otherwise organic rich clayey silt background sediment. Spatial trends in physical properties, sedimentary features, grain size percentiles and deposit thickness are compared for the two lakes and possible causes are discussed. The two lakes record the tsunami event from 1960, but do so differently from each other, because of their different topographic and bathymetric setting. Both lakes are suited to reconstruct the tsunami recurrence for the west coast of Chiloé.

Linking Subduction-Earthquake Supercycles with Mountain Building in the Region of the Giant 1960 Chile Earthquake

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Ranges in magnitude and recurrence of subduction-zones earthquakes allows them to be grouped into earthquake cycles within supercycles. Placing prehistoric as well as historical ruptures within such cycles of differing scale is necessary to evaluate the seismic hazard of plate boundaries. Linking these cycles with patterns of permanent forearc uplift will leas to improved models of plate-boundary segmentation. We use coastal stratigraphy and soils on raised intertidal deposits at Isla Guafo – 60 km landward of the south Chile trench – to infer land-level changes associated with great subduction earthquakes, and numerical models to infer the relations of the changes with plate-boundary slip. Guafo was uplifted ~4 m during the 1960 earthquake (M9.5) and has been subsiding rapidly since (20 mm/yr from 3 yr continuous

GPS). Five soils, each developed on coseismically uplifted intertidal deposits, were buried during the past 1.7 ka. The sequence of soils and deposits suggests land-level changes similar to those observed during and after 1960. Such repeated changes can be modeled as elastic strain accumulation and release in plate-boundary zones A and B (Lay's zonation). Distinct changes in coastal morphology and stratigraphy suggest Gaufo was permanently uplifted during an earthquake in AD 681–887 (2sd). This age range overlaps the time when a sequence of subsided buried soils at Maullín (140 km from the trench) shows an abrupt change in lithology suggesting uplift. If the change records permanent uplift at Maullin during the same earthquake, slip in zones A, B and C is required. Emerged Holocene beach ridges and even higher Pleistocene marine terraces may be evidence of the permanent uplift resulting from earthquakes of this type. Such giant events rupture down to the continental mantle and may have millennial recurrence times instead of centuries as for 1960-type events.

Two Centuries of Emergence in Northern Chiloé Before Sudden Submergence Associated with the Giant 1960 Chile Earthquake

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Analysis of soundings recorded on old nautical charts indicates that the north end of Chiloé Island, located midway along the rupture of the giant 1960 Chile earthquake, emerged by two meters or more during the two centuries preceding 1960. This region, about 125 km landward of the Chile Trench, subsided coseismically about 1.8 m in 1960. Charts were analyzed from 1770, 1790, 1896, and 1922 and the average differences in water depth (and thus relative sea level) were calculated relative to a modern hydrographic survey made in 1986. Issues associated with georeferencing the historical charts are relatively minor, except for a portion of the chart from 1770. Implied elevations and standard errors of the mean differences relative to 1986 are -1.1 ± 0.4 m, -0.7 ± 0.2 m, $+1.3\pm0.1$ m, and $+1.7\pm0.1$ for 1770, 1790, 1896 and 1922, respectively. The influence of varying chart datum, however, remains to be fully characterized and at a minimum will increase the uncertainty. Rapid emergence in this region was inferred by Charles Darwin from his finding in 1834 of shells of the intra-tidal boring mollusk Pholas in place in their holes – with grass growing in them – above the limit of high tides. The implied average uplift rate between 1770 and 1922 is about 18 mm/yr, on the high end of uplift rates predicted by elastic models, but generally consistent with the interseismic deformation expected above the locked megathrust between the overriding South American Plate and the subducting Nazca Plate converging at the rate of 66 mm/yr.

Understanding Mega-Earthquake Related Tsunami on Subduction Zones without Large Historical Events

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Following on the megathrust earthquake related tsunami in Chile in 2010 and in Japan in 2011, the insurance industry has become very aware of tsunami as a catastrophic peril. Though little exposure is currently covered for tsunami risk, insurers and their clients are interested in understanding the risk and having a tool to price this peril. To begin the process of understanding tsunami as a risk peril, Risk Management Solutions Inc. (RMS) is developing a global suite of tsunami inundation footprints. Many of these events represent well studied historical events including the events in 2010 and 2011. The dataset will also include a series of M9 events on subduction zones that have not historically ruptured in M9 events. These scenarios are to account for the potential risk posed by subduction zones that may be underestimated. This concern was raised following the 2011 Tohoku Japan M9 that far exceeded the expected maximum magnitude on the Japan Trench of M8.4 that was constrained based on the historical record.

Subduction zones without M9 historical events being modeled include the Makran Trench, the Lesser Antilles Arc and the Hikurangi Trench. The source characterization follows the unit sources used to develop the NOAA propagation database. The number of unit sources and the slip per unit source are defined based on the event magnitude (i.e., M9) and consideration of the subduction zone segmentation. For these events with no historical information, there is little seismological data to constrain the distribution of slip across the unit sources. We are running a series of tests using the COrnell Multi-grid COupled Tsunami Model (COMCOT) to develop intuition about the interaction of the slip distributions with the extent and characteristics of the modeled inundation footprints. The goal is to develop a series of footprints that will guide insurers to understanding their exposures most at risk to tsunami inundation in different parts of the world.

Great Earthquakes and Tsunamis during the last 1000 years in the Kodiak Segment of the Alaska-Aleutian Megathrust

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The eastern segments of the Alaska-Aleutian megathrust are source areas of significant seismic hazards, generating great earthquakes and tsunamis that may propagate across much of the Pacific Ocean. Source areas include the Prince William Sound and Kodiak segments, which ruptured together during the M9.2 great Alaska earthquake of 1964, and the Semidi segment, that ruptured in 1938, with a M8.3 earthquake. Paleoseismic evidence from coastal sediments provides a good record of the recurrence of these large events, with widespread evidence of great earthquakes through the last 6000 years in the Prince William Sound segment. Less is known about the recurrence of great earthquakes in the Kodiak and Semidi segments. Here we present new paleoseismic data that, combined with archaeological and historical records, reveal two previous ruptures of the Kodiak segment; in AD 1788 and 492-350 cal BP. We identify the AD 1788 event in sediments of three estuaries. Diatom-based transfer functions from multiple cores across the sites estimate similar amounts of coseismic submergence at each estuary, $\sim0.35\pm0.26$ m (2σ). Two of the estuaries have tsunami sediments associated with this event.

We suggest that the Kodiak segment ruptured on at least 4 occasions in the past 900 years, each time causing measurable land surface deformation and generating tsunamis capable of travelling across the Pacific. In AD 1964 the Kodiak segment ruptured with the adjacent Prince William Sound segment. In 1788 it was probably a single segment rupture, although others have suggested co-rupture with the Semidi segment. The 492-350 cal BP earthquake and tsunami is only recorded, so far, in the Kodiak segment. Although the evidence in Kodiak is sparse for older events, current thought is that $\sim$880 cal BP the Kodiak, Prince William Sound and probably the Yakataga segments ruptured together.

Same Asperity, Different Rupture Pattern: Variations in Holocene Splay Fault Motion from Seward to Middleton Island, Alaska

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Using tsunami run up, seismic reflection and bathymetric data, we identify tsunamigenic sea floor ruptures beneath the Gulf of Alaska from the 1964 M9.2 earthquake. Coseismic sea floor ruptures are rooted in faults that appear across the 500-km wide Gulf of Alaska continental shelf. Seismic and geochronology data suggest that this asperity, located at the trailing edge of the subducted Yakutat terrane, has remained in place for thousands of earthquake cycles. However, we show evidence that these faults produce a range of uplifts during consecutive earthquakes.

Based on estimated tsunami travel times from 1964, we identify thrust faults that produced 5–10 m wave heights in the coastal town of Seward and along the Kenai Peninsula. We identify the Hanning Bay, Patton Bay, Cape Cleare, and Middleton faults as local tsunami sources. These faults moved vertically upwards of 12 m during the 1964 earthquake, but paleoseismic data provide no evidence that other late Holocene earthquakes produced such uplifts on the adjacent Montague Island. Additionally, new seismic evidence suggests offsets across a prominent late Holocene(?) unconformity show significant variations in fault slip for the past few earthquakes. The Cape Cleare and Patton Bay faults, with (post-glacial) sea floor scarps as large as 69 m and 25 m respectively, likely accommodates the greatest vertical uplift within the asperity region. Another highly active thrust fault, termed the Middleton fault, hosts a west-east 100 km long $>$20 m high sea floor scarp. Uplift along this fault is likely responsible for 3.5 m raised shoreline on Middleton Island from the 1964 earthquake and the total sea floor scarp height likely includes uplift from at least the prior 3 earthquakes that individually produced 6–9 m marine terraces on Middleton Island. Although rapid exhumation results from repeated coseismic slip on multiple faults, slip distribution between earthquakes is highly variable.

Field Studies of the 2012 Mw 7.7 Haida Gwaii Tsunamigenic Thrust Earthquake: Implications for Paleoseismic and Paleotsunami Studies of Subduction Zones

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On 28 October 2012, Canada's second-largest recorded earthquake occurred on a thrust fault offshore western Haida Gwaii, British Columbia. The Mw 7.7 earthquake caused little damage, largely due to the limited infrastructure of the islands and their low population, concentrated almost entirely on the eastern side. Despite a lack of witnesses to large waves, field studies in the weeks and months following the event have provided evidence of significant tsunami runup on the west coast of Haida Gwaii, exceeding 3 m (above state of tide) along ~200 km of the coastline, exceeding 6 m (maximum 13 m) at the heads of several bays and inlets. Tsunamis of this size elsewhere have proved devastating to populated and low-lying coastlines. The impact of the Haida Gwaii tsunami was determined mainly by the presence, landward of the forest edge, of debris with an oceanward origin, some of it caught in tree branches or draped over logs. Most debris was manmade (plastic, polystyrene, etc), with much seaweed also present within a few months of the tsunami. Muddy deposits were present in some locations, but sedimentation was clearly not proportional to runup, and the apparent lack of sand can likely be attributed to the absence of an offshore source. Limited GPS data and field measurements of elevation-dependent sessile organisms indicate coseismic subsidence of up to ~0.5 m at west coast sites between 52.25 and 53.0 N. The paleoseismic history of the predominantly strike-slip Haida Gwaii margin is unknown, and no large tsunamigenic thrust earthquakes had occurred in previous historical time. However, the potential magnitude, recurrence and tsunami hazard of such earthquakes can be approximated from various geophysical constraints. Our findings suggest that the 2012 event will leave very little in terms of a stratigraphic record, underscoring both the ephemeral record of sub-magnitude 8 events at other subduction zones and the importance of multidisciplinary hazard analyses.

The 1861–2005 Simeulue–Nias Slip Patch of the Sunda Subduction Zone: Characteristic Slip on an Otherwise Non-characteristic Megathrust

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Using precise ^{230}Th-dated coral microatolls to infer uplift of Sumatra's outer arc islands, and hence slip on the underlying plate interface, we have developed paleoseismic histories at numerous sites along a 900-km stretch of the Sunda megathrust off the west coast of Sumatra. In earlier work, by comparing the records along strike, we identified two persistent barriers to earthquake rupture. Simeulue, a 100-km-long island off the west coast of northern Sumatra, straddles the boundary between the 2004 (M_W 9.1) and 2005 (M_W 8.6) Sunda megathrust ruptures and acted as a barrier to both. Historical and coral paleoseismic records suggest that central Simeulue has behaved as a persistent barrier for at least the past 1100 years. Farther south near the Equator, the Batu Islands patch of the megathrust has been a barrier to rupture in great earthquakes from both the south (1797, 1833) and north (1861, 2005).

Our most recent paleoseismic results, from the 2005 rupture patch off the west coast of northern Sumatra, indicate that the 1861 rupture appears to be nearly identical in extent to the 2005 rupture, involving uplift of Nias, Bangkaru, and the eastern half of Simeulue. At three sites where the 1861 uplift has been well determined, it was comparable to uplift locally in 2005. Our limited knowledge of an earthquake around AD 1422 is consistent with characteristic slip in that earthquake as well. The 2005 Simeulue–Nias rupture patch appears unique along the Sunda megathrust in its tendency toward characteristic behavior. As we have seen elsewhere along the Sunda megathrust, we document evidence for time-varying rates of interseismic subsidence over portions of the 2005 rupture patch.

Stratigraphic Evidence of the 2004 Sumatra-Andaman Subduction Zone Seismoturbidite

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The paleoseismic history of earthquakes along subduction zones is an important tool to evaluate the cyclic hazards that millions of coastal residents are exposed to globally. From the R/V Roger Revelle, we sampled the sea floor with 109 gravity, Kasten, piston and trigger pair, and multi-cores offshore of Sumatra. We use litho- and chrono-stratigraphic methods to correlate turbidites between cores in sedimentologically isolated accretionary prism slope basins and trench settings. In 12 cores we interpret the uppermost turbidite to have been deposited as a result of seismic shaking related to the 2004 earthquake. Measures of relative age (lack of hemipelagic sediment of oxidation in the core tops) and radiometric ages (^{210}Pb and ^{14}C) support our interpretation of the uppermost turbidite. P_Sequence (OxCal software) age modelling results in an age of -60 ± 10 cal yrs BP. The 2004 deposit is imaged in reflection data including the resolution of repeated coarse Bouma Tb-Tc subunits within the 2004 bed. There is evidence that there may be cycles of large turbidites similar in size to the 2004 seismoturbidite below our cores. Triggering distances at core sites outside the 2004 rupture zone are quite short (<50 km), which we attribute to high attenuation, rupture directivity, and low or no slip at the southern segment boundary. Using our correlations for the stratigraphic history spanning the last 6.5 ka, we estimate recurrence of earthquakes in the region of the 2004 earthquake to be 260 ± 160 years. Down-core variations of interseismic intervals show similar trends between cores, supporting our correlations. Recurrence of trans-oceanic paleotsunami records in the northern Indian Ocean is between 280 and 320 years, consistent with our estimate. Records of earthquakes in the submarine environment, found in sediment cores and seismic reflection data, are a useful tool to evaluate the cycling of strain along subduction zones.

Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales

Oral Session · Wednesday · 8:30 AM · 30 April · Room 3
Session Chairs: Marco Pilz and Nori Nakata

Temporal Changes in Near-Surface Shear Wave Velocity

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Temporal changes in shear wave velocity are analyzed at the Wildlife Liquefaction Array (WLA) and Garner Valley Downhole Array (GVDA), located in southern California. These densely instrumented geotechnical and structural engineering field sites continuously record both acceleration and pore pressure, with accelerometers located on the surface and at various depths below the surface, and pore pressure transducers installed at depth within the liquefiable layers. Permanently instrumented structures for examining soil-foundation-structure interaction and a permanent cross-hole array at the sites have transformed these sites into multi-disciplinary earthquake engineering research facilities. Over the last decade, local and regional seismic activity, including multiple extremely active earthquake swarms, have produced a valuable new data set providing a unique opportunity to observe site response, and temporal changes in shear wave velocity, at an unprecedented level of detail. In addition to the earthquakes provided by nature, active testing experiments using the mobile shakers from NEES@UTexas and NEES@UCLA, a permanent remotely controlled shaker, and a cross-hole hammer source, have produced an equally valuable data set that can be used to examine temporal changes in site response and shear wave velocity. Nonlinear soil behavior associated with the larger events recorded at these sites is analyzed in terms of changes in travel times between accelerometers in the array for the largest ground motions, as well as a reduction in high frequency amplification for these events. The location of accelerometers at the surface and at additional depths throughout the soil column provides the opportunity to examine the contribution of the various layers to the overall site response. Significant changes in shear wave velocity (>30%) during the largest events are observed, as well as smaller season changes (~5%) related to water table fluctuations.

Monitoring Temporal Changes in a Levee with Ambient Seismic Noise

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In the US, nearly 200,000 km of earth levees and 85,000 earth dams provide flood protection, clean water supply and renewable energy for millions of people. Earth dams and levees (EDLs) are prone to a costly cause of failure in the form of internal erosion of soils within the structure. This progressive failure seeks out areas of weakness in EDLs due to inferior construction and/or aging. It is invisible to current methods of inspection until it manifests itself on an exterior surface.

There is a critical need to implement of a cost effective system that can (1) identify internal weakness or damage in EDLs during early stages when intervention can prevent catastrophic damage and cost, and (2) broadly assess the tens of thousands of km of EDLs within the US and globally.

A relatively recent geophysical method, called ambient noise correlation or seismic interferometry, allows reconstructing the seismic impulse response of the subsurface between two geophones. Using only the ambient vibration of the earth, this method does not rely on the costly and time consuming use of an active source, and allows continuous monitoring of the structure at test.

In Fall 2012, we deployed an array of geophones on a full scale levee (IjkDijk), built and tested to failure by our Dutch collaborators. Using seismic interferometry, we are able to reconstruct impulse responses between each pairs of geophones, all along the 6 day test. We can then monitor changes in waveform and wave velocity during the test to assess mechanical changes occurring inside the structure. These changes show a good agreement with the visual and geotechnical parameters acquired during this known sequence of failure.

Shallow 3D Velocity Imaging by a Joint Rayleigh- and Love-Wave Noise Tomography

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Imaging shallow subsurface structures and monitoring related temporal variations are two of the main tasks for modern seismology. Although many observations have reported temporal velocity changes e.g. in fault zones, in volcanic areas and on landslides, precise measurements of velocity changes based on passive sources like ambient seismic noise still suffer from high computation times. Recently, we presented a method (Pilz et al. 2012, 2013) to overcome this problem for obtaining information about the local subsoil structure on the engineering scale.

Here we present a fast one-step inversion procedure which accounts for the topographic relief and which is based on the computation of high-frequency correlation functions for both Rayleigh and Love waves between stations of a small-scale array deployed for recording ambient seismic noise. Constitutively, a tomographic inversion of the travel times estimated for each frequency is performed in due consideration of the different depth-sensitivity kernels of both Rayleigh and Love waves. We test our technique by using numerical simulations of seismic noise for a realistic site and by using real-world recordings from a small-scale array performed at Solfatara (Italy). The results imply that the method can provide a clear image of the subsurface structures and that, in turn, passive seismic interferometry allows local structural heterogeneities to be satisfactorily reproduced. In particular, the use of Love-wave phase velocities allows to further constrain the inversion and to improve the resolution of the model. Since reliable velocity estimates for the frequency range investigated can be obtained in almost real time, the results further imply the use of the proposed procedure as an exploration and monitoring tool.

Developing 3-D Shear Wave Models using a Multi-Objective Joing Inversion Scheme

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Understanding Earth's tectonic processes requires determining the Earth structure, and we focus on determining Texas tectonic processes employing a joint inversion scheme for multiple geophysical datasets. In particular, we expand on a constrained optimization approach for a joint inversion least-squares (LSQ) algorithm to characterize a one-dimensional Earth's structure, We use seismic data from regional networks in Texas and the USArray, a dense network of permanent and portable seismographs placed systematically across the continental United States. We collect and process seismic data (receiver function, surface wave, body wave travel times), plus collect gravity data from other efforts. By jointly inverting these four geophysical data sets, we can avoid the inherent non-uniqueness from inversion.The Multi-Objective Optimization Problem (MOP) technique enables the capability to combine linear and non-linear problems. The technique enables the combination of inhomogeneous data sets and different statistical properties of error associated with each data set. We chose to use the MOP optimization approach because we want to find the best possible solution for our nonlinear geophysics inverse problem. We prove through numerical and experimental testing that our MOP scheme performs inversion in a more accurate, robust, and flexible matter than traditional inversion approaches. To develop quasi 3-D models, we interpolate the 1-D results using a kriging approach, only when we have excellent station coverage. Our quasi 3-D velocity models provide insight into the tectonic history and physical properties of the Earth structure of Texas, and we will compare mantle structure beneath Texas to other ancient and active rift systems.

Joint Modeling of Complementary Data Functionals for Seismic Site Characterization

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New approaches suggest that it may be possible to determine shallow Earth structure through low-cost, non-invasive seismic surveys that make use of ambient noise and that the results can be used for 'shake-casting' to produce scenarios for the purposes of urban planning, improving community resilience, and emergency response. We will present a strategy for determining seismic 'site characterization' through joint modeling of horizontal to vertical spectral ratios (HVSR) and surface wave dispersion, determined via spatial autocorrelation (SPAC), refraction microtremor (ReMi), and/or multi-channel analysis of surface waves (MASW). Fitting of data functionals by synthetics is driven by global optimization and the models are assessed quantitatively. The products of this approach are shear wave velocity profiles for the shallow subsurface, accompanied by posterior probability distributions and parameter correlation matrices.

Optimization strategies for solving nonlinear problems in geophysics have several advantages over linearized inversions. Jointly fitting dispersion curves and HVSR functionals via global optimization allows us to characterize the space of possible models, assess model reliability, identify parts of the 'best-fit' model that are poorly constrained, and guide us toward new data that might improve constraints on the model. Tools such as the posterior probability distribution and the parameter correlation matrix allow us to assess the relative contribution of both types of data to model constraints and how to choose the optimal weights between data types.

The joint modeling technique is applied to data acquired in an NSF-funded Pan-American Advanced Studies Institute in Santo Domingo, Dominican Republic, entitled 'New Frontiers in Geophysical Research: Bringing New Tools and Techniques to Bear on Earthquake Hazard Analysis and Mitigation', as a proof-of-concept survey in a highly built-up urban environment.

The Virtual Eruption of Okmok Volcano, Alaska

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When Okmok Volcano erupted violently in 2008, the new cone it formed swallowed a broadband seismometer within the caldera at site OKCD. The destruction of the seismometer constituted a short-term loss in terms of monitoring capability during the ensuing month-long eruption; however, in hindsight it has allowed the volcanic tremor source to be investigated using a novel technique in seismic interferometry known as the virtual earthquake approach (Denolle et al., 2013; JGR). In the case of Okmok, we refer to the technique as the virtual eruption.

The virtual eruption is based on the ability to obtain accurate Green's functions between the eruptive source and seismic stations using ambient noise cross-correlations. At Okmok, the local network consisted of 7 working stations during the 2008 eruption with a total of 11 components. Station OKCD existed for 4 years prior to the 2008 eruption. Over that time period, ambient noise derived Green's functions can be computed between OKCD and the 7 operative stations from the 2008 eruption. In contrast to synthetic Green's functions modeled computationally with an assumed subsurface velocity structure, these Green's functions are exact so long as the noise sources are sufficiently well distributed in azimuth. Path effects

due to unknown 3D heterogeneity are captured in the Green's functions. The 2008 Okmok eruption lends itself nicely to the analysis since low frequency tremor, within the frequency band from 0.2–1 Hz, radiated continuously from beneath the new cone. Backprojection of the low frequency tremor demonstrates that it was predominantly composed of surface waves. Thus, the tremor and ocean noise share the same wave type and frequency range, further enabling the application of the virtual eruption technique. Green's functions can be obtained for both a force and/or moment source and the eruptive source process estimated continuously over time with waveform inversion.

Nonlinear Elasticity and Slow Dynamics Observed at the Factor Building (UCLA-California) by Processing Continuous Recordings

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During earthquakes, a structure may suffer damage, ultimately changing its elastic properties. Earthquake engineers simplify building response by describing it as bi-linear behaviour. The appearance of cracks in the building materials during events causes a transient variation of Young's modulus, a variation which becomes permanent if irreversible damage occurs. Frequency and damping are closely related to the system's Young's modulus and, assuming constant mass, control its dynamic response according to Newton's second law. Monitoring these values therefore enables the assessment of rapid damage to the structure, or nonlinear response, in situations such as after an extreme event, or slow deterioration due to ageing (Structural Health Monitoring). However, real data also reveals a sometimes slow recovery of the structure's elastic properties when stress returns to a very low level. The origin of this recovery is not clear. In this study, we will show that under slight internal deformation, the elastic parameters of the Factor Building (UCLA California) follow a nonlinear elasticity regime, typical of a slow dynamic. We found that using very precise measurement of frequency and damping under slight stress, these parameters are modified by around 0.1% for deformation levels of the order of 10–7. These observations tend to confirm the universal nonlinear elastic behaviour of actual systems, comparable to that of rock or soil, as observed in laboratory conditions. Our results show that the dynamics of a structure composed of composite material and linked to the ground, are similar to those of an Nonlinear Mesoscopic Elasticity material, which had not been considered previously. Our observation will enable better understanding of the dynamic response of structures; changes in design and constructi

Seismological Monitoring of a Tall RC Building in Nice, France

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The main goal of the National Building Array Program (NBAP), supported by both the French Ministery of Ecology, Sustainable Development and Energy and the French Ministery of Land Planing and Housing and managed by the French Accelerometric Network (RAP) is the seismic response analysis of typical French buildings for seismic vulnerability assessment purposes. In the frame of NBAP, GEOAZUR laboratory and CEREMA institute set up a seismological array in a tall reinforced concrete (RC) building raised in 1979 and located in a sedimentary basin in the city of Nice, southeastern France. The building is a 67-meters high tower composed of 20 levels and 2 basements. The structure is made of concrete slabs connected to two kernels that include the staircases and the elevators. Since july 2010, the building has been monitored by 24 accelerometric sensors distributed along the building elevation. This array is recording continuously, authorizing us to analyse both the ambiant vibrations and the ones due to local seismicity. We present here the first results obtained on the dynamic behavior of the building inferred by these data. About 10 earthquakes have been recorded in 2011–2012 with magnitude ranging between 4.0 and 6.1, all of them situated at epicentral distances greater than 40 km from the building. These earthquakes only produced weak motions in the building and didn't cause any visible damage in the structure. In the longitudinal direction of the building, three modes of deformation are detected with frequencies around 1.2 Hz, 5.3 Hz and 9.3 Hz respectively. These eigenfrequencies show little variation with respect of the considered earthquake. We also investigate the frequency variation of the first mode throughout the year using the ambiant vibration recordings. Our first analyse indicates that this frequency may slightly vary during the year, but this variation is not larger than one standard deviation.

Noise-based Crustal Seismic Velocity Changes associated with the 2011 Tohoku-oki Earthquake

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The occurrence of the giant 2011 Tohoku-oki earthquake and its record by the dense Japanese Hi-net seismic network provide a unique opportunity to study the response of the Earth's crust to strong shacking and deformation. Here, we use one year of continuous seismic data from the Hi-net network in Japan to estimate noise-based crustal seismic velocity changes associated with the occurrence of the 2011 Mw9 Tohoku-oki earthquake. We present results obtained from correlations in the 0.1–0.9 Hz frequency range and for lapse time up to 60 s. We observe a strong coseismic drop of seismic velocities (up to 0.2%) in volcanic regions throughout Japan, including Mt Fuji Volcano about 400 km away from the epicentral area of the Tohoku-oki earthquake. This is the prominent feature of the response during the first days after the earthquake. The velocity drop increased in the following days in the region of maximum deformation produced by the earthquake, followed by a phase of slow recovery. We compare the temporal response of the crust in Japan after Tohoku-oki earthquake with the one observed in Sichuan basin and Tibet after the 2008 M7.9 Wenchuan earthquake (Froment et al., 2013, Obermann, 2013). In both cases, the results indicate that, beyond a relaxation of the non-linear effect on the seismic speed, post seismic processes affect the seismic velocity at depth.

Depth Constraint of Velocity Changes caused by the 2011 Tohoku-Oki Earthquake

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The 2011 Mw9.0 Tohoku-Oki earthquake caused changes in near-surface seismic velocities, which are measured by computing transfer functions of small earthquake data recorded by the Japanese strong-motion recording network, KiK-net. Although this analysis works well and one can estimate changes in velocities all over Japan, the estimated changes are averaged values over the depth of KiK-net borehole receivers. Also, intervals of time-lapse measurements depend on how often earthquakes occur. Here, we analyze surface waves of ambient-noise data observed by the high sensitivity seismometer network (Hi-net) using cross-coherence techniques and discuss the depth constraint of the changes in velocities. Ambient noise is suitable for time-lapse measurements because of their continuity. After cross coherence, we obtain traveling waves from one station to another station. To enhance the signal-to-noise ratio in higher frequencies, we employ the adaptive covariance filter, which is a noise-suppression filter. Then we apply coda-wave interferometry to the cross-coherence functions and estimate the changes in velocities between two time intervals (before and after the Tohoku-Oki earthquake) at each frequency. Since the frequency of surface waves relates to the depth penetration of the waves, we can invert the depth variation of the changes. For this inversion, we also use the changes estimated from KiK-net data. With these analyses, we find that most of the changes occur in the very near surface.

Fault Structure, Heterogeneity, and Implications for Rupture Dynamics

Oral Session · Wednesday · 1:15 PM · 30 April · Room 3
Session Chairs: Thomas H. W. Goebel, Thibault Candela and Heather Savage

BIEM Simulation for Anti-Plane Dynamic Rupture Propagation across a Bimaterial Interface

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Boundary Integral Equation Method (BIEM) enables us to simulate dynamic rupture propagation on non-planar faults under some assigned stress conditions with high-precision. Although applicability of BIEM had been limited only for rupture in a homogeneous medium, we modify it for anti-plane rupture in a 2-D bimaterial. For the modification, we treat a discretized fault element embedded in the bimaterial and derive an analytical solution that represents radiated waveforms of stress components due to a sudden slip on the element.

Our method extends a simulation of dynamic rupture propagation to the case of a fault that intersects with a bimaterial interface. In our results, we find that temporal increase or decrease of slip velocity goes back from an intersection of the fault and the interface toward a nucleation point after a rupture front reaches the intersection. A sign of the temporal change is consistent with a sign of reflected wave that depends on material contrasts. Hence our results are qualitatively feasible and comprehensible in view of an elastic wave theory. Magnitude of the change is, however, not easy to predict because reflection coefficients have complicated dependence on a spatiotemporal relationship between a wavesource and a receiver. For example, in a case of a frictionless fault, we confirm that slip velocity temporally takes negative value when the temporal decrease of slip velocity passes.

Temporal change of slip velocity can cause more complicated behaviour of faulting under a strongly rate-dependent friction law. Under the friction law, temporal increase/decrease of slip velocity leads weakening/strengthening of friction and vice versa, so that positive feedback works. We suggest a possibility of reactivation or deactivation of slip off a rupture front by considering our results and the friction law.

3D Dynamic Rupture Simulation Across a Complex Fault System: The Mw7.0, 2010, Haiti Earthquake

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Earthquakes ruptures often take places on faults adjacent to – and sometimes very close to – major plate boundary faults without activating them. The 1989 Loma Prieta earthquake is a classic case where rupture occurred on a blind reverse fault (with both dip-slip and strike-slip) while the adjacent San Andreas Fault was not triggered. In this study, we investigate the rupture dynamics of the Haiti earthquake in a complex fault system with multiple segments as identified by the aftershock relocations. We calculate a background stress regime that is consistent with the type of motion on the Léogâne rupture and with the regional tectonic regime. We initiate nucleation on the eastern segment of the Léogâne fault, at the location of the relocated earthquake centroid, by defining a circular region of 2-km radius where shear stress is slightly greater than the yield stress. By varying friction on faults and background stress, we find a range of scenarios that are consistent with the observed rupture. In the absence of near-field seismic records of the event, we score the models against the static surface deformation field derived from GPS, InSAR, and coral uplifts. All the plausible simulations show that the rupture propagates from the eastern to the western segment of the Léogâne fault, but not on the Enriquillo fault nor on the Trois Baies fault. The best-fit simulation shows a significant increase of shear stresses on the Trois Baies fault, consistent with aftershocks observed on this fault. This best-fit simulation also shows a significant increase of shear stresses mostly on the top and on the western part of the Enriquillo fault indicating that it has been brought closer to rupture and still constitutes a threat for southern Haiti. We also find that a shift of the western segment of the Léogâne fault by about 2 km to the north compared to recent studies provides a better fit to the coseismic InSAR and GPS displacements.

Dynamic Rupture Models of Earthquakes on the Bartlett Springs Fault, Northern California

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The Bartlett Springs Fault is a major right-lateral component of the San Andreas fault system in northern California. Fault slip-rate models inferred from GPS data [Murray et al., 2013] and alignment array data [McFarland et al., 2009] both indicate that the Bartlett Springs fault experiences aseismic creep. We use the three-dimensional finite element computer code of Barall [2009] to conduct models of dynamic spontaneous rupture on this fault, both to determine characteristics of potential earthquakes, and to gauge the ability of rupture to propagate in the creeping regions. Within the framework of slip-weakening friction, we represent locked portions of the fault as regions of positive stress drop, and creeping regions as having zero or negative stress drop. Using the fault geometry and creep distribution from studies by Murray et al., we examine simulations that implement either homogeneous initial stresses or a regional stress field, along with several different parameterizations of the contrast in frictional properties between locked and creeping zones. We compare the earthquake source characteristics for the same fault geometry with and without the known creeping sections. These comparisons can be used to estimate the impacts of the creeping sections on ground motion predictions.

Stick-slip Instability in Granite Initiated as Acoustic Emission Event

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Recent modeling studies have explored whether large earthquakes begin with a detectable nucleation phase, or if such a phase can be accelerated or skipped by the rupture of a smaller fragile fault patch in a 'cascade-up' process. To explore such a condition in the laboratory, we study the initiation of dynamic rupture on a fault in a 76 mm diameter cylindrical granite laboratory sample. The simulated fault is a smooth saw cut surface inclined at 30 degrees to the sample axis and was deformed at confining pressures of 40–120 MPa. In a sequence of 10 stick-slip instabilities, we measure radiated seismic waves using piezoelectric sensors glued directly on the granite sample and located inside the pressure vessel. For each stick-slip, the radiation of seismic waves (>20 kHz) appears to initiate abruptly, and we can locate the hypocenter. In many cases, we find that the beginning is relatively weak, and that the first few microseconds of the seismic records are nearly indistinguishable from those of many other very small magnitude discrete seismic events, commonly known as acoustic emissions (AE), that occur in the seconds prior to each large stick-slip. In this sense, it appears that stick-slip begins as an AE event that rapidly (~20 microseconds) grows about two orders of magnitude in linear dimension and ruptures the entire 150 mm length of the simulated fault. Yet, in many cases, the AE events that appear to initiate stick-slip are neither exceptionally large nor in unusual locations compared to other AEs that occurred in the previous seconds and *did not* dynamically grow into stick-slip instabilities. We also find indications of accelerating fault slip in the final seconds before stick-slip which could reduce fault strength and therefore allow an AE to grow into a larger rupture.

Seismic Moment Tensors and b-values of Acoustic Emissions During Stick Slip Sliding Tests

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We investigate processes governing stick-slip frictional sliding in laboratory experiments performed on Westerly Granite sample. We perform full moment tensor and b-value analysis using full waveform acoustic emission (AE) data from two stick-slip experiments with different initial fault state: saw-cut and rough surface. AE activity was recorded continuously throughout the experiment at 10MHz sampling rate using 16 piezoelectric P-wave sensors glued directly to the surface of the cylindrical specimens providing good spatial coverage. About 100,000 AE events were recorded in both experiemnts out of which more than 43,000 were located using the time-dependent 1D anisotropic velocity model. We compute full moment tensors and b-values from AE events that occurred in close temporal proximity to stick-slip events. The full moment tensors were calculated using first P-wave amplitudes and the recorded waveform amplitudes were corrected for coupling quality and incidence angle. We decomposed full moment tensors into isotropic/CLVD/double-couple components and used shear-tensile source model to examine changes in source mechanisms before and after stick-slip events. In addition, temporal and spatial changes in AE magnitude-frequency distribution b-value were analyzed. We observe microfracturing processes are clearly driven by the initial state of the fault (saw-cut/rough surface). In case of the saw-cut sample the rotations of full moment tensor P and T axes plunges are visible and attributed to the existence of scarce non-double-couple seismic events preceding the stick-slip phases and can be well explained applying the shear-tensile source model. For the rough surface sample an intensive shear-enhanced compaction of the comminuted material is seen in moment tensor derived parameters as well as in increasing b-values. Also, the AE-derived slip distribution is more complex prior to stick-slip events compared to postfailure slip in both cases.

Fault-Zone Maturity Defines Maximum Earthquake Magnitude

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Estimating the maximum likely magnitude of future earthquakes on transform faults near large metropolitan areas has fundamental consequences for the expected hazard. Here we show that the maximum earthquakes on different sections of the North Anatolian Fault Zone (NAFZ) scale with the duration of fault zone activity, cumulative offset and length of individual fault segments. The findings are based on a compiled catalogue of historical earthquakes in the region, using the extensive literary sources that exist due to the long civilization record. We find that the largest earthquakes (M~8) are exclusively observed along the well-developed part of the

fault zone in the east. In contrast, the western part is still in a juvenile or transitional stage with historical earthquakes not exceeding M=7.4. This limits the current seismic hazard to NW Turkey and its largest regional population and economical center Istanbul. Our findings for the NAFZ are consistent with data from the two other major transform faults, the San Andreas fault in California and the Dead Sea Transform in the Middle East. The results indicate that maximum earthquake magnitudes generally scale with fault-zone evolution.

The Role of Iquique Area in a Future Large Earthquake - A Multi-disciplinary Approach

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It is supposed, that the Iquique Seismic Gap in northern Chile is capable of producing earthquakes of any large magnitude between 7 and 9 depending on which seismic cycle is active at the moment. Two scenarios are most likely to succeed: one that causes a follow-up event of the 1877 earthquake supposed to be a magnitude 9 event, and another one in which several M 7 – 8 events subsequently fill the seismic gap. Whichever of the two scenarios apply, the Iquique area will play a role in it. One of the major questions we want to target in this project is whether the respective area could act as a segment boundary or an asperity structure.

In previous work, we compared post-seismic spatial b-value distributions with isostatic residual anomalies of the gravity field to identify co-seismically ruptured asperities of the 1995, Mw 8.1 Antofagasta earthquake at the southern tip of the Iquique seismic gap and did the same with the 2007, Mw 7.9 Tocopilla earthquake. Now we want to apply the same method to the Iquique area where we maintain the mixed broadband- short period Iquique Local Network with 20 stations in total, monitoring small to intermediate sized background seismicity. Taking into account GPS-, tiltmeter-, creepmeter data and results from new density modelling, first results show that the Iquique area behaves differently from the adjacent areas to the north and the south.

Fully Automated Real-time 3D Earthquake Locations in the San Jacinto Fault Zone Using High Resolution 3D Velocity Models

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We present an automated real-time earthquake location algorithm based on eikonal travel time solutions and apply it to the seismically active San Jacinto Fault Zone. Building on previous tomographic work, we create both Vp and Vs velocity models for the San Jacinto region at 100m uniform grid spacing. Based on these models, we use the finite-difference eikonal-based fast marching method to create a library of 189 station-centric travel time maps. Though computationally expensive, this is only done during initial setup; further travel time computation is only necessary when the velocity model is updated or when new stations are added. Because the travel times are stored in a binary structured grid format, and the values at each station are stored at common grid points, retrieval of the travel time for potential hypocenter locations is very fast. Starting with an initial earthquake location based on 1D velocity models, and using as input observed first-motion data, we perform a grid search on the 3D travel time maps to minimize the misfit for all stations. Once a best-fit grid point has been located, we optimize the earthquake location to the sub-grid scale using trilinear interpolation. We apply this methodology to the seismically active San Jacinto Fault zone, where a dense network of real-time seismic instruments has been recently upgraded.

Imaging Tremor Dynamics at the San Andreas Fault near Parkfield with a Mini Seismic Array

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Slow earthquakes and tremor play an important role in fault motion and stress release. How slow earthquakes and their regular counterparts (fast earthquakes) interact, and its implications on the fault dynamics remains poorly understood. Addressing these issues require spatially complete imaging of seismic activity, both slow and fast, with a high level of detection. I installed a mini seismic array at the San Andreas Fault between Cholame and Parkfield to achieve these objectives. This is a very suitable area as it is seismically productive, breaks repeatedly to produce damaging M6 fast earthquake, and produce prolific tremor and fast earthquakes in close proximity. So far, two months of array data has been analyzed using beam-backprojection (BBP) algorithm [Ghosh et al., 2012; Ghosh et al., 2009].

The BBP algorithm using the solo mini array detects 5 times more duration of tremor activity compared to a standard method using conventional seismic network [Nadeau and Guilhem, 2009]. The array scans the entire fault plane, about 100 kms alongstrike, from SE of Cholame to NW of Parkfield. The spatially complete array imaging of tremor reveals a highly tremor active area under Cholame, CA, which has been documented by previous studies [Nadeau and Guilhem, 2009; Shelly et al., 2009]. In addition, I also observe comparable duration of tremor activity near Parkfield. In other words, tremor distribution alongstrike the SAF shows bi-modal distribution with two peaks of comparable tremor duration. I also observe rapidly propagating tremor streaks, both towards and away from the Parkfield rupture patch. Tremor streaks are observed frequently, and seem to be a fairly common mode tremor migration, similar to Cascadia [Ghosh et al., 2010]. The mini array is capturing a wide spectrum of seismic radiation from the SAF with unprecedented sensitivity, and providing high-resolution and spatially complete image of seismicity from a major plate boundary strike-slip fault.

Slip Characteristics of the Deep Portion of the San Andreas Fault Inferred from Low-Frequency Earthquakes

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The dynamics of fault slip in the lower crust are just beginning to be understood due to the recent discovery of non-volcanic tremor (NVT) and Low Frequency Earthquakes (LFEs). These phenomena occur in the deep crust where material properties are more ductile than in the brittle upper crustal seismogenic zone. Here we examine timing characteristics of LFE repeating sources of the deep crustal slip along the Parkfield segment of the San Andreas Fault (SAF). We apply an automatic LFE burst detection algorithm to all the LFE repeating sources to track the similarity and dis-similarity in source behaviors. We show that LFE repeating sources are comprised of bursts whose timing may be highly regular, highly irregular or intermediate in nature. We show further the coherence of burst activity among different sources varies along SAF, suggesting strong and weak coupling of different patches of fault. By comparing the observations to laboratory biaxial shear experiments, we infer possible complex slip regimes in the deep crust that vary along the fault, indicating that some portions exhibit stick-slip behavior, some are stably sliding, and others have a mixed slipping behavior.

Site Response: From Site-Specific Analyses to Predictive Models Around the Globe

Oral Session · Wednesday · 8:30 AM · 30 April · Room 4
Session Chairs: Eric Thompson and Dominic Assimaki

Array Measurements of Rayleigh-Wave Amplitudes to Estimate Site Response

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Many traditional measures of site response rely on separate characterization for each individual site. However, with dense seismic array data becoming more available, it is becoming feasible to make use of these array data to jointly estimate site amplification at all stations. Here, we discuss one method for such a joint estimation. Our methodology, which relies on Rayleigh waves approximately satisfying the 2D wave equation, takes measurements of the amplitudes and travel times of Rayleigh wavefields and decomposes these fields into wave propagation terms and local amplification terms. This method accounts for amplitude differences caused by complex wave propagation and therefore provides an estimate of local site response that is minimally biased by distant 3D structure. Further, these terms represent direct observations of the amplitude variations across the region, and do not require inverting for complicated 3D velocity models or the use of wave propagation simulations. The technique can be applied to both earthquake and ambient noise correlation data, and we show results applied to a number of different arrays that

span a wide range of spatial and temporal scales. At the small scale, we analyze data from the 5000-component Long Beach array and 2500-component Santa Fe Springs array in the densely populated Los Angeles Basin, and show that the array data show significant variability in site response over spatial scales of a few hundred meters. At the large scale, we analyze longer period (5–100 s) data from USArray, which also show significant variability in long-period site response over distances of hundreds of km.

The Importance of the Elastic Half Space Assumption in Site Response Analysis

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The influence of local soil conditions on the nature of earthquake damage has been recognized by seismologists and engineers for many years, especially after the Mexico City and Loma Prieta seismic events in 1985 and 1989, respectively. One of the fundamental decisions when conducting an equivalent linear site response analysis involves the determination of the depth and characteristics of the elastic half space (EHS). This boundary condition is usually defined at bedrock level and implies that the portion of the energy of downward-propagating seismic waves that are refracted into the EHS will be completely absorbed by the rock mass. Thus, the waves reflected from deeper material boundaries in the actual geologic profile are not considered in the numerical site response. For sites where a strong soil-rock impedance contrast is present, the EHS is typically set at this depth, with the EHS shear wave velocity often assumed to be approximately 800 m/s in the western US and approximately 3000 m/s in the eastern US. However, a case history of a site in the US that has significant shear wave velocity reversals (as a result of multiple sequences of basalt flows and sedimentary interbeds) will be presented to show that for less usual profiles, the determination of the EHS depth and characteristics is no longer intuitive nor trivial. In fact, results from a series of 1D equivalent linear site response analyses performed for the site, reveal that just the presence of a strong impedance contrast is not enough for determining the appropriate EHS depth in the numerical analyses. A parametric study is conducted to investigate which factors have the strongest influence on the EHS assumption.

Site Response Mapping with Fewer Proxies

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Site response is frequently estimated through empirical correlations with the time-averaged shear-wave velocity to 30 m (Vs30), and empirical correlations have been developed to predict Vs30 from mapped quantities such as surface geology, topographic slope, or terrain. This creates an unnecessary "weak link" in the site response map, which we eliminate by correlating empirical amplification function (EAFs) directly to surface geology and topographic slope. By eliminating the unnecessary link of Vs30 between the mapped proxy and site amplification, we eliminate some uncertainty in the site response map. An additional benefit of focusing on EAFs is to achieve the best possible estimate of the site response at strong motion stations; site-specific EAFs at stations that have recorded numerous ground motions reflect the actual site response rather than approximations based on Vs30 or the correlations of EAFs. This will be particularly useful for ShakeMap when correcting recorded motions to reference rock motions, which are used to interpolate between stations. The use of EAFs for correcting recordings to rock conditions will improve the underlying rock reference layer of ShakeMap, which is currently estimated from recorded ground motions that are adjusted to rock conditions with Vs30-based corrections. Estimating nonlinearity is a key challenge to employing EAFs for larger ground motions. To address this, we select the representative Vs30, which is the Vs30 that minimizes the misfit between the EAF and the empirical site response equations. The representative Vs30 then determines the nonlinear factors that modify the EAFs for large-amplitude motions.

Validation of Site-Specific Response Models using KIK-Net Ground Motion Recordings

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Our ability to predict site response in regional ground motion simulations is constrained to a large extent by the scarcity of velocity profiles. To overcome this issue, site response is accounted for in terms of trends, parameterized by site stiffness proxies such as $V_{s,30}$. This approach is adequate for broadband ground motion models that capture high-frequency ($>$1Hz) components – that is, the frequencies mostly affected by site response – in terms of trends as well. Physics-based ground motion simulations, however, provide deterministic predictions of broadband time-series that cannot be corrected for site response by means of spectral amplification ratios. To validate the high-frequency predictive capabilities of these models, it is important to account for the fine resolution of the geotechnical layers, and for the nonlinear effects of these layers in the time domain. In this talk, we present a validation study of four 1D site-specific response models that can be used to modify ground motion time-series for seismic wave amplification in layered media. We test both linear frequency-domain and nonlinear time-domain solutions on the site scale, by comparing surface predictions to observations at 30 KIK-Net stations that have recorded several strong events, including the 2011 Tohoku earthquake. Velocity profiles are used as the only input to all models, while additional parameters such as quality factor, density and nonlinear dynamic soil properties are estimated from empirical geotechnical engineering correlations. Thus, differences in site-specific response predictions are attributed to the model capabilities rather than to differences in input parameters. We use validation metrics that are of interest in both seismology and engineering, including bias ratios of peak ground response and visual comparisons of elastic spectra, on the one hand, and inelastic to elastic deformation ratio for multiple ductility ratios, on the other hand.

Site Effects in Concepcion Basin: Geometry and Amplification from Gravity and Microtremors

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The city of Concepcion suffered significant damage during the February 27, 2010, great Maule earthquake. The magnitude of that event was evidently a major factor. However, observed damage distribution in the city was irregular and not related in a straightforward manner to construction quality. Site effects are suspected to be a major factor. However, during the main shock only two seismic records were obtained in the area. In this paper, we present a site effects study of Concepcion. We gathered available information related to site response and subsoil structure. This includes: geologic history and interpretation regarding the basin structure, gravity measurements, and previous seismic noise studies using both single measurements and array of stations. In addition, we performed microtremor measurements. The data were analyzed using the standard horizontal-to-vertical spectral ratios (HVSR) for single station records, and SPAC and seismic interferometry for data from arrays. The first results consist of a dominant period and maximum amplification maps derived from HVSR. We show that, in the case of Concepcion, amplification values derived from HVSR are significant and useful to understand site effects. Dominant period shows an excellent correlation with the basin structure derived from gravity measurements, suggesting that site effects are governed by the impedance contrast between the sediments and the underlying basement, and that sediments spatial variability is relatively low. Array microtremor measurements allowed estimating shear wave velocity profiles in the sediments. Preliminary simulations are in good agreement with amplitude estimates from HVSR. Our results will be used to explore the relation between damage distribution during the Maule earthquake with the variability of ground motion due to the irregular subsoil structure.

PRENOLIN Project: A Benchmark on Numerical Simulation of 1-D Non-Linear Site Effect. 1 –Site Selection for the Validation Phase

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The main objective of the PRENOLIN project is the assessment of the uncertainties associated to non-linear simulation of 1D site effects. An international benchmark is underway to test several numerical codes including various non-linear behavior models to compute the non-linear seismic site response. A preliminary verification phase (i.e. comparison between numerical codes on simple, idealistic cases) will be followed by a validation phase comparing the predictions of such numerical estimations with actual strong motion recordings obtained on well-known sites. The benchmark presently involves 23 different teams and 28 different non-linear computations.

The site selection for the validation phase has been done within the KiK-net and the PARI (Port and AirPort Research Institute) Japanese networks. The purpose of this presentation is to detail and discuss the criteria that were used for this slection: (1) Sites must have recorded strong and weak events. (2) Sites must

have a 1-D geometrical configuration (i.e., horizontal layering): in the linear range the numerical and instrumental site response must agree. (3) The down-hole station must not be too far from the surface (depth <250 m). (4) the sites must have a large non-linear soil behavior and preferentially not associated to pore pressure effects (such as cyclic mobility or liquefaction) to allow the consideration of total stress numerical codes and (5) the local conditions should allow to drill complementary holes to measure the actual NL. Three sites were selected out of an initial selection of about 50: one from KiK-net (KSRH10) and two from PARI (Onahama and Sendai). Specific in-situ and laboratory tests are being performed at the selected sites to have a complete characterization of the linear and non-linear site parameters.

PRENOLIN is part of two larger projects: SINAPS@, funded by the ANR, the French national research agency, and SIGMA, funded by a consortium of nuclear operators (EDF, CEA, AREVA, ENL).

Analysis of Local Earthquake Data from Delaney Park Downhole Seismic Array, Anchorage, Alaska

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Under the Advanced National Seismic System of the U.S. Geological Survey, Delaney Park downhole seismic array was installed in 2004 to understand the effect of seismic wave propagation in the near surface sediments of downtown area of Anchorage, Alaska. Out of seven tri-axial accelerometers, one sensor is located on the surface and other six are installed inside the boreholes at the depth of 4.5 m, 10 m, 18 m, 30 m, 45.5 m and 61 m, respectively. The accelerometers are connected with four 24-bit Quanterra Q330 digital data recording systems and the data are sampled at 200 samples per second. To delineate 1-D layered earth structure at the array site and to understand geotechnical properties of these layers, we have analyzed the recorded borehole data from local earthquakes (ML= 3.5–5.0). Each recorded data sets were first filtered using a 4-pole band-passed Butterworth filter between 0.01- 5.0 Hz. A combined implementation of reflectivity method with a global optimization algorithm has been used to compute the response of the 1-D model. The reflectivity method calculates the synthetic SH, SV and P- waves seismograms at each sensor location for a given source–receiver pair. The optimization algorithm determines the optimal model parameters (e.g., P- and S-wave velocities, densities and thicknesses) of the layered earth model that produces synthetic waveforms which 'best fit' the observed data. The combined cross-correlation criterion between the vertical, radial and transverse component of the data and synthetics in a specified time window has been adopted to determine the optimal model. The results indicate that the presence of 15–20 m thick soft sediments (commonly known as Bootlegger Cove Formation) with a relatively low S-wave velocity (210–270 m/sec) at a depth around 25 m significantly amplifies the S-wave motions at the array site. However, no reduction in P-wave velocity across this formation is noticed and thus the amplification of the P-wave is negligible.

Lessons Learned from Conducting Seismic Site Response Analyses that Require Explicit Consideration of the Site Attenuation Parameter

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In response to the accidents at the Fukushima Daiichi nuclear power plants following the 2011 Great Tohoku Earthquake and subsequent tsunami, the Nuclear Regulatory Commission (NRC) established a Near Term Task Force (NTTF). Following recommendations suggested by the NTTF, the NRC issued a 50.54(f) letter that requested that licensees and holders of construction permits under 10 CFR Part 50 reevaluate the seismic hazard at their sites against present-day NRC requirements. The Electric Power Research Institute (EPRI) developed the "Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic" document, which outlines the process of evaluating seismic site response for nuclear sites and when the site attenuation parameter (κ_0) should be explicitly considered in seismic site response.

Typically, κ_0 is implicitly included in the site response through consideration of the input motion and layers of soil and rock. However, as the site depth increases, the potential to exceed the expected value of κ_0 increases, and thus the contribution of κ_0 provided by the site profile (κ_0) needs to be explicitly considered. We recommend that κ_0 be measured from the acceleration transfer function computed using small-strain linear elastic material properties, instead of evaluating the response spectral shape of the motion. Our studies indicate that in 1D site response analysis κ_0 is dependent only on the travel time and damping of the profile, and not on the relative differences in velocity (i.e., velocity reversals are not influential). The κ_0 can then be adjusted by modifying the damping of linear material at depth, which may result is unexpectedly small damping values.

Seismic Site Amplification in the Port Hills during the Canterbury Earthquake Sequence: Case Study of Critical Slopes

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Significant ground failure and building damage occurred in the hillside suburbs of Christchurch during the Mw 6.2 February and Mw 6.0 June 2011 earthquakes. Damage patterns indicate that local amplification of ground motions likely contributed to the most severe effects. The Canterbury earthquake sequence provides an internationally significant case study to understand the influence of amplification effects in areas of steep topography.

We present analysis of ground motion variability in the Port Hills focussing on a case study across a critical slope and deep-seated landslide above the suburb of Sumner. Our observations from small-scale temporary seismometer arrays show strong differences in ground motion polarization and amplification up to 3 times PGA over small distances (tens to hundreds of metres). Synthetic ground motion simulation of 2D amplification effects suggests site effects result from both topographic shape and material properties. Our results have engineering implications, given that all sites are classed as rock under current New Zealand design standards. At present in New Zealand such amplification effects are not routinely taken into account when designing earthworks or structures on slopes or in landslide risk assessments.

Calibration and Evaluation of Response Spectra in the Downtown Area of Anchorage, Alaska

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Alaska's most populous city, Anchorage, is located within a seismically active region including the Pacific Megathrust subduction zone and crustal faults on the North American Plate. A complex geology of glacial till, Bootlegger Cove Clays, and alluvium exists within the Anchorage area. Significant damage resulted from the response of the Bootlegger Cove Clays to the 1964 Great Alaska Earthquake. Downtown Anchorage is located primarily in the thick deposits of the Bootlegger Cove Clays and is susceptible to significant ground loss during a similar event. Strong and weak motion stations have been constructed at more than 40 sites across Anchorage. In addition to strong motion monitoring stations, shear wave velocity profiles have been developed to further characterize a number of these sites. Six sites across downtown Anchorage have been selected for model calibration and evaluation of response spectra. In an attempt to characterize the soil response, a one-dimensional equivalent linear model has been developed and calibrated using measured spectral responses for ground motions of approximately 0.1g and soil properties, including measured shear wave velocities for several sites in the vicinity of downtown Anchorage. After calibrating the model, input ground motions from five selected deep subduction zone earthquake ground motions and ground motions measured at Anchorage's downhole array were applied to the base of each of the six site-specific models and the transfer functions at each site were compared. The five selected ground motions had PGAs of between 0.3g and 0.4g. The resulting equivalent linear models were used to evaluate the effects of ground motion attenuation due to the alluvial soils and Bootlegger Cove formation found in downtown Anchorage.

The results from the evaluation show the notable effect of the Bootlegger Cove formation and alluvial sediments on the surface response to the input ground motions.

Pillars of Simulation: Seismic Velocity and Material Models

Oral Session · Wednesday · 2:15 PM · 30 April · Room 4
Session Chairs: Ricardo Taborda, Po Chen and En-Jui Lee

Seismic Wavefield Simulations of Earthquakes within a Complex Crustal Model for Alaska

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We explore the effects of two major sedimentary basins (Cook Inlet and Nenana) on the seismic wavefield in Alaska, in preparation for an iterative tomographic inversion using spectral-element and adjoint methods. Our 3D reference seismic velocity model contains three geometrical interfaces: the Moho surface, the basement surface of the sedimentary basins, and the topographic surface. The crustal and upper mantle tomographic model is from Eberhart-Phillips et al. (2006), but modified by removing the uppermost slow layer and then embedding models for the two major

sedimentary basins. Synthetic seismograms are computed using the spectral-element method. We quantify the accuracy of the initial 3D reference model by comparing 3D synthetics with observed data for several earthquakes originating in the crust and underlying subducting slab.

We explore the effect of complex crustal structure on the seismic wavefield of the 1964 Mw 9 earthquake source model of Ichinose et al. (2007), which was obtained using geodetic data, tsunami arrival times, and teleseismic P waves recorded from the earthquake. Cook Inlet basin has a prominent effect on the seismic wavefield in southern Alaska. This 8-km-thick sedimentary basin is situated between Anchorage and a major portion of the ~700-km-long rupture of the subduction interface. The relatively large simulation region can be used to test different scenario megathrust earthquakes as well as different models of the 1964 earthquake.

Full-3D Waveform Tomography for Crustal Structure in Southern California using Earthquake Recordings and Ambient-Noise Green's Functions based on the Adjoint and the Scattering-Integral Methods

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We apply a unified methodology for seismic waveform analysis and inversions to Southern California. We developed a semi-automatic seismic waveform analysis algorithm for full-wave earthquake source parameters and tomographic inversions. The algorithm is based on continuous wavelet transforms, a topological watershed method, and a set of user-adjustable criteria to select usable waveform windows for full-wave inversions. The algorithm takes advantages of time-frequency representations of seismograms and is able to separate seismic phases in both time and frequency domains. The selected wave packet pairs between observed and synthetic waveforms are then used for extracting frequency-dependent measurements, which are used in our seismic source and structural inversions.

Our full-wave waveform tomography uses the SCEC Community Velocity Model Version 4.0 (CVM-S4) as the initial model, a staggered-grid finite-difference code to simulate seismic wave propagations. The sensitivity (Fréchet) kernels are calculated based on the scattering integral and adjoint methods to iteratively improve the model. We use both earthquake recordings and ambient noise Green's functions in our full-3D waveform tomographic inversions. To reduce errors of earthquake sources, the epicenters and source parameters of earthquakes used in our tomographic inversion are inverted by our full-wave CMT inversion method. After 26 iterations, our improved model (CVM-S4.26) shows many features that relate to the geological structures at shallow depth and contrasting velocity values across faults. The velocity perturbations could up to 45% with respect to the initial model in some regions and relate to some structures that do not exist in the initial model, such as southern Great Valley. The waveform misfits reduce over 70% when compared with that at the initial stage. The new tomography enables more accurate physics-based seismic hazard applications and the tectonic reconstruction of Southern California.

Validation of Physics-Based Ground Motion Earthquake Simulations Using a Velocity Model Improved by Tomographic Inversion Results

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We present validation results of a set of ground motion simulations done for the case study of the 2008 Mw 5.4 Chino Hills earthquake using an improved version of the Southern California Community Velocity Model (CVM-S4). The improved version of the model, called CVM-S4.26, includes perturbations obtained from a 3D waveform tomographic inversion of the crustal structure of the region. Advances in computational seismology have made it practical to solve geographically large seismic forward and inverse wave propagation problems. Inverse problems are, however, more computationally intensive than forward simulations, so they are often done at lower resolutions than individual forward simulations. Common regional forward wave propagation simulations are done up to maximum frequencies as high as 4 to 5 Hz, whereas full waveform tomographic inversions are resolved at much lower frequencies, often less than 0.5 Hz. There is an increasing scientific interest in incorporating inversion results in higher frequency forward simulations. We have implemented three different interpolation schemes to recover information discarded from the original model (CVM-S4) prior to the inversion process, and integrate the (coarse grid) perturbation dataset from the inversion back into the model, to be able to create arbitrary resolution velocity meshes out of the improved model (CVM-S4.26). We present initial results from simulations that use the new velocity model and test the level of improvement seen in the validation of the ground motion synthetics for the case of the Chino Hills earthquake. Although the simulation of a single event offers only a limited perspective about the changes seen after the integration process, they shed light on the potential of using coarse inversion results in high-resolution simulations for the region.

Stochastic Descriptions of Fine-Scale Basin Velocity Structure from Well Logs and the SCEC Community Velocity Model (CVMH)

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The trend of numerical wave propagation studies to higher frequencies (> 2 Hz) has created a demand for higher resolution velocity models. Thus, we are developing a statistical description of fine-scale velocity structure, informed by local borehole observations and geological correlations, with the goal of enhancing community models so that they can support higher-frequency simulations. We examined the velocity (v_p) structure in 108 wells across the Los Angeles basin and within a large oil field in the same region that provides more than 400k velocity samples from 70 deviated wells. These logs sample velocity to approximately 1m scales; the field is also constrained by 3D seismic reflection data. After trend removal and despiking, the data show symmetric distributions of velocity variability relative to the CVMH centered around a mean of 0% and with standard variations of 6.5% to 6.9%. The distributions are highly non-Gaussian: the kurtoses are high with values of ca. 13 in aggregate and up to 50 in individual wells. Using logarithmic frequencies, there is a linear drop-off from the mean to both sides indicating a power-law distribution of velocity variability. Second-order, but potentially important features include a small upward curvature on the log-log plot, indicating a fatter-tailed distribution than a simple power law, and an asymmetry in this curvature about the mean value. Vertical correlation lengths are on the order of 80 m. Further, the dense data sample suggests that horizontal correlation lengths are about 25 times that of vertical correlation lengths, defining a highly anisotropic nature of basin velocity structures. Finally, we show that lateral velocity structures are more highly correlated along stratigraphy than in the horizontal dimension in areas of dipping beds. This suggests that stratigraphic horizons may provide a means to guide the implementation of a stochastic description of fine-scale velocity structure in the basin models.

Rupture Dynamics and Ground Motions from Earthquakes in Heterogeneous Media

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Our goal is to better understand the origin of complexity in the earthquake source process, and to quantify the relative importance of source complexity and wave scattering along the propagation path in causing incoherence of high frequency (1–10 Hz) ground motion. In previous work, we found that off-fault material heterogeneities (random variations in density and elastic moduli) in the near-fault region of our dynamic rupture models have little influence on the rupture process. Here we study how medium heterogeneity influences ground motions in the near-source region (few tens of km from the fault). Heterogeneity exists at all wavelengths; we perform numerical experiments to determine which wavelengths influence seismograms. By generating a suite of media with identical power spectral densities below some wavelength, we isolate contributions from long-wavelength heterogeneity. The similarity of the resulting waveforms indicates that only heterogeneities of wavelengths less than ~100 m influence near-source ground motions. This is because 1–10 Hz waves are appreciably scattered only by heterogeneities at scales comparable to their wavelength. At these short wavelengths, geostatistical data on material properties indicate that the power spectral density (PSD) function follows a power law. Our findings indicate that neither standard deviation nor correlation length alone appropriately quantify the amplitude of medium heterogeneity, and we instead define a single amplitude factor that specifically quantifies the power-law portion of the PSD. We also note that for realistic levels of heterogeneity, scattering at all wavelengths has little effect on ground motion intensity measures such as PGA, PGV, and RMS accelerations, in the near-source region.

Couple-Stresses in Elastodynamics and Quantitative Seismology

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Nearly all of the developments in quantitative seismology have at their roots the fundamental concepts of force-stresses and force-tractions, as first presented by Cauchy in the middle of the 19th century. At that time, Cauchy had in mind an underlying atomistic model having only central forces. As a result, he was able to eliminate the need for couple-stresses and couple-tractions in constructing his elemental stressed tetrahedron. We now recognize, of course, that the atomistic world is far more complicated. Even prior to the twentieth century, Voigt postulated the existence of non-central forces and couple-stresses. However, a fully consistent continuum theory incorporating these ideas has been difficult to realize.

What would be the effect of introducing couple-stresses and couple-tractions into elasticity theory? Within the field of quantitative seismology, we might ask the following. What impact would this have on wave propagation? Would there be any consequences for fracture mechanics?

In this paper, we explore these questions within the context of consistent couple stress theory, as developed recently in Hadjesfandiari and Dargush (2011, 2012, 2013). This theory resolves long-standing issues of indeterminacy, which plague previous theories, by demonstrating that the couple-stress tensor is skew-symmetric, along with its energy conjugate deformation measure, the mean curvature tensor. In general, we find that angular momentum balance has a much more important role in this theory and that wave propagation and crack tip mechanics may be affected significantly. The paper begins with a brief overview of this new theory and then focuses on these two fundamental problems.

Physical Characterization of Seismic Attenuation in Earth Models

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Seismic attenuation represents an important part of Earth's models at all scales, from lab experiments with rock samples and engineering applications to mantle flows, free oscillations of the whole Earth, and tides. At present, all attenuation models are formulated in terms of the quality factor (Q), which is a specialized property attributed to the materials in order to explain the internal friction occurring during deformation. Special 'principles' for solving attenuating-wave problems (Boltzmann's and correspondence principles) and rules for their implementation in numerical modeling (such as memory variables) are constructed to implement this model. However, these principles do not automatically agree with physics. The Q factor is a phenomenological property that may not always successfully represent all aspects of internal friction. Examples where the Q model can be problematic include: 1) distribution of frictional stresses in poroelastic media, 2) conservation of energy in surface waves, and 3) zero attenuation within the liquid outer core. To resolve such problems, we do not rely on the Q and the associated viscoelastic 'principles' and propose direct use of physical laws, such as the solid and fluid viscosity, thermoelasticity, poroelasticity, and other. This approach was used in early attenuation studies by Jeffreys, Knopoff, and Ricker, and it readily follows from classical continuum mechanics and thermodynamics. Time-integral relations for 'material memory' are replaced with instantaneous differential equations including frictional forces, and the 'frequency dependences of Q' are explained by the dependences of physical mechanisms (such as viscosity) on strains and strain rates. This approach guarantees causality and conservation of energy, and it is naturally implemented in finite-difference (FD) and finite-element algorithms. The approach is illustrated on FD modeling of wave propagation in a medium with nonlinear viscosity.

Anelastic Attenuation and Elastic Scattering Models of the Los Angeles Region for Use in Earthquake Simulations

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The accuracy of earthquake simulations needed for physics-based seismic hazard analysis depends on good information about crustal structure. As the frequencies increase, seismic wave attenuation becomes more important. We compare attenuation models that have been recently used in the CyberShake hazard model (Graves et al., 2011) and other simulation studies for the Los Angeles region (Olsen et al., 2009; Taborda & Bielak, 2013) with constraints from local earthquake data out to 10 Hz, which include those from Hauksson & Shearer's (2006) attenuation tomography as well as our own measurements. We show that the velocity-attenuation scaling relationship for shear waves employed by CyberShake ($Q_S = 50V_S$) provides a good approximation to the average crustal structure at $f = 0.3$ Hz, but it does not capture the lateral variations in Q_S at shallow depths. Moreover, this frequency-independent model is inconsistent with the high Q_S values observed throughout most of the crust at $f > 1$ Hz. The data indicate a frequency-dependent attenuation of the form $Q_S \sim f_\gamma$, where $0.5 = \gamma = 0.8$. Anomalously low Q_S factors are observed at very shallow depths, which can be explained by a combination of anelastic attenuation and elastic scattering. The scattering parameters are roughly consistent with small-scale, near-surface heterogeneities observed in well-logs and seismic reflection surveys in the Los Angeles basin. Observation of small-scale heterogeneities from well-log shows strong non-Gaussian distribution (A. Plesch & J. Shaw), so scattering effect on attenuation must be described by using a Non-Gaussian model. We summarize the observations in a new attenuation and scattering model for the CyberShake region that is laterally heterogeneous and frequency dependent.

Regional Phase Attenuation in the Iranian Plateau and Surrounding Regions

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We have constructed and validated regional wave (Pg, Sn, and Lg) attenuation models for the crust and upper mantle throughout the Iranian plateau and surrounding regions. This research has increased ray path coverage of critical areas and help to create robust regional phase amplitude and attenuation models. We have recently combined our Iranian data set that with our existing Middle Eastern Lg waveform database. Together, these two data sets give us reasonably good coverage of the northern Middle East using both a two station and reverse two station (RTM) attenuation measurements. Furthermore, using the RTM measurements we have been able to effectively isolate the site excitation terms across the northern Middle East. These terms have demonstrated in part where we have problems with the station instrument response and in other regions where we have anomalous amplification of high frequency waves due to local geology. We have also processed Pg waveforms in order to obtain robust estimates of Qp in the crust within the Iranian plateau. In general we have found a good correlation between Lg and Pg Q values with the exception of northwestern most Iran.

We have also developed an Sn attenuation model using two station measurements of Q for long period Sn (0.5 to 0.1 Hz) and for high frequency Sn (0.5 to 2 Hz). The Sn Attenuation Tomographic models at low frequency (0.3 Hz) and high frequency (2 Hz) are somewhat different across the northern Zagros which is consistent with P wave tomography results. This difference can be explained by the high frequency Sn traveling more as a true head wave along the Moho and the low frequency Sn dives down to depths of 100 to 150 km in the uppermost mantle.

Finite-frequency Sensitivity of Seismic Waves to Fault Zone Structures

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We analyze the volumetric sensitivity of fault zone seismic head and trapped waves by constructing finite-frequency Fréchet kernels for these phases based on idealized and realistic velocity models. We first validate numerical calculations by waveform comparisons with analytical results for a model with a bimaterial fault interface separating different elastic solids. After establishing numerical accuracy up to 10Hz, we construct sensitivity kernels for a 'vertical sandwich' model where a narrow low-velocity region is surrounded on either side by a higher velocity material, along with a suite of velocity models based on detailed tomographic results from the San Jacinto Fault Zone. In contrast to P body waves, which have little or no sensitivity to fault zone structure, the sensitivity kernels for head waves have sharp peaks with high values near the fault in the faster medium. Surface wave kernels show the broadest spatial distribution of sensitivity, while trapped wave kernels are extremely narrow with sensitivity focused entirely inside the low-velocity fault zone layer. Taken together, these phases contain complementary information about fault zone and regional velocity structure. These results indicate that adjoint tomography using high-frequency head and trapped waves kernels, combined with traditional body and surface wave kernels, can constrain fault zone structure at higher range of scales than has previously been possible.

Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks

Oral Session · Wednesday · 8:30 AM · 30 April · Room 7/8
Session Chairs: Bruce Beaudoin and Christopher Bruton

Cold, Wet Seismology: Lessons from Instrumenting Temperate Glaciers

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In the past decade, glaciology has seen resurgence in the use of passive seismology to investigate ice dynamics. Seismology has been particularly useful in elucidating the mechanics of iceberg calving – which presents a large knowledge gap in understanding future changes in global sea level. Unstable calving margins are characterized by rapid ice flow, extreme deformation, massive failure events, and remote locations, all of which challenge traditional instrumentation methods. Even at substantial distance from calving margins, where deformation presents less of a problem, mitigating installations under Alaskan weather conditions presents a formidable challenge. It is common for installation sites to receive upwards of 4 m water equivalent snowfall during winter, followed by 8 m water equivalent of summer melt. Maintaining operational conditions for sensors, especially those deployed in ice, has proven to be an iterative process. In this presentation we will highlight lessons learned in site geometry, power systems, deployment strategy, and complimentary measurements to better aid future experiments in polar and sub-polar environments.

Maximizing the Scientific Utility of Broadband Data from Polar Regions

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Recent advances in engineering for power systems, enclosures, and communications by individual investigators and community facilities have made possible the year-round operation of seismometer systems at high polar latitudes. These advances open possibilities for both temporary and long-term observing in remote regions not previously accessible to seismologists, but potentially of great scientific value. Logistics and equipment costs are typically high in such settings, and the costs must be justified by the quality and value of the data returned. Data completeness and integrity, metadata validity, and signal quality are affected by seismic-system engineering and deployment strategies, which trade off with logistics limitations. Here, we consider the effect of such engineering and deployment strategies on data quality, with examples from temporary and long-term seismic deployments, as well as lessons learned from deployments of polar geodetic instrumentation.

Polar Seismology: Engineered Solutions from the IRIS/PASSCAL Instrument Center

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The IRIS/PASSCAL Instrument Center at New Mexico Tech established a directed effort to address the complexities of deploying seismic equipment in Polar environments in 2006. A joint NSF MRI with UNAVCO to develop power and communications solutions for Antarctic deployments initially funded the effort. This development focused on: dual primary/secondary battery power systems, enclosures to maintain temperatures within the equipment's operating specifications, Iridium communications for state-of-health, minimizing logistics, and working with manufacturers to encourage the development of purpose-built equipment for Polar environments. These early efforts realized increases in data return for year around deployments from roughly 50% to over 90%. With continued NSF support, IRIS/PASSCAL has been able to continue to refine and modify these early designs and enhance PI success. Coupled with this continued development is a new generation of equipment that is more suited to the Polar environment. Our presentation will highlight both IRIS/PASSCAL's current engineered solutions for Polar environments and explore future directions in light of emerging technologies.

Ongoing Developments in the Plate Boundary Observatory Alaska Network: Testing New Telemetry and Power Options for Improving Station Robustness

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The Alaska component of the NSF-funded Plate Boundary Observatory network (PBO-AK), operated and maintained year-round by UNAVCO, consists of 138 continuous GPS stations, 12 co-located tiltmeters, and 41 telemetry relay stations spread across the state. Most PBO-AK stations have a telemetry system, which allows for daily data downloads and remote state-of-health monitoring under normal operating conditions. Over the initial 5-year operations and maintenance phase, greater than 95% of possible GPS data have been recovered from PBO-AK. During this period, station robustness and data recovery rates have increased, while latencies have generally decreased. These trends may be attributed to improvement of power, telemetry, and equipment enclosure designs, as well as PBO staff's increasing experience in the logistics of working in Alaska's diverse field environments.

We present several case studies of successful and failed strategies to develop a robust, low-maintenance system for deployment in the wide range of climate regimes experienced throughout Alaska. Recent projects include the operation of 3 EFOY methanol fuel cells, replacement of VSAT terminals with more wind- and animal-resistant Inmarsat BGAN equipment, testing of QuadLS web relays, and installation of a cold-rated DSL modem in Interior Alaska. Operation of the PBO-AK network also frequently includes addressing changes implemented by ISPs and equipment manufacturers, which may have positive and/or negative impacts on system performance.

Extensive experience in the logistics of supporting small team fieldwork in Alaska has improved our efficiency and lowered risk levels (with respect to team safety and accurate budgeting) for network operations. Recent cross-training of PBO-AK staff with UNAVCO's Polar group has provided opportunities to evaluate the applicability of polar station design concepts to sub-arctic continuous GPS systems around Alaska.

Tracking Telemetry State of Health with Nagios

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The Alaska Earthquake Center maintains over 150 real-time seismic stations in Alaska, supported by a vast telemetry network spanning thousands of miles and including more than 300 individual IP-addressable devices such as radios, routers, and modems. Because of the cost and difficulty of accessing most field locations, it is important to closely monitor communications equipment remotely. This makes it easier to diagnose station outages if they occur, and even provide advanced warning of potential telemetry problems.

In November 2013 we established a monitoring system using Nagios, an open-source network monitoring software package. Our Nagios setup checks ping response times to IP-addressable devices on our network. In addition, it uses SNMP queries to obtain extra information provided by certain devices. In particular, we monitor voltage, temperature, signal-noise, and reflected power on most of the radios on our network. Tracking this information over time is critical in evaluating radio link performance, and will allow us to better focus our maintenance efforts during the short Alaskan field season.

Development of Next Generation Field Methods for Portable Broadband Seismic Arrays

Oral Session · Wednesday · 10:45 AM · 30 April · Room 7/8
Session Chairs: Timothy Parker and David E. Hawthorn

Normal Modes: Investigating Signal and Noise Phenomena Across Instrument Types and Deployment

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Whether a seismic signal in a certain frequency band can be detected in a recording depends primarily on four factors: the amplitude of the signal at the site, the conditions at the site which affect the ambient noise in that band, the sensitivity and self-noise of the sensor in the band, as well as the sensitivity and self-noise in the digitizer in the band. For the very long period band, between 1.0 and 5.5 mHz, the normal modes provide an excellent signal for exploring the effects of the latter three contributions, since after a large or great earthquake, their amplitudes are similar all over the earth. In the past, observatory equipment in an observatory setting were required to observe them. We observed normal modes in the 1.0–5.5 mHz band with good signal-to-noise ratio in the aftermath of the Mw 8.3 Sea of Okhotsk deep earthquake on 24 May 2013 at many stations of the Berkeley Digital Seismograph Network and at other stations in other networks. They are equipped with a variety of sensors, including those with a flat passband extending to frequencies lower than the normal modes, and digitizers. They are also deployed in a variety of geologic settings, including cabled ocean bottom stations, like MOBB in California, the Japanese cabled "Dense Ocean-Network for Earthquake and Tsunamis (DONET)" and the IODP seafloor borehole in the south of Japan. The sites have varying physical

infrastructure and site preparation. We explore the factors contributing to the observation of the normal modes on vertical and horizontal components at a suite of amplitudes of excitation (based on recent earthquakes with magnitudes between 7 and 8.3). Signal-to-noise ratios for the normal modes are seen to vary more by deployment type and location than by instrumentation.

An Analysis of the Tradeoffs Between Seismometer Performance and Convenience

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There are a multitude of different broadband seismometers of varying periods and performance specifications. Scientists often have the unenviable task of selecting the best equipment to suit a broad range of applications. We provide a high level view of some of tradeoffs available to the sensor design team that directly impact the utility of the final product. We further review the importance of these specifications with respect to selected use cases and give examples demonstrating where tradeoffs in certain performance specifications can pay dividends in ease of deployment and numbers deployed. We consider an example in an oil and gas exploration setting. The network was deployed with the mandate of detection and location of magnitude 1 to 4 events within a localized zone (20 km). The deployed network of 20 second broadband seismometers is able to fully meet the objectives of the network. The increased tilt tolerance and reduced size of the 20 second instruments greatly simplified the installation process. Furthermore, we find that the switch to 120 second period seismometers provides little or no benefit in the context of the goals of the network. In this instance the added utility of the smaller 20 second instrument outweighed the performance gains of the larger 120 second instrument. We conclude that the seismometer with the lowest noise floor and broadest frequency band is not always the best choice of instrument.

What Should I Do with the S13? - Or Better: How to Teach New Tricks to an Old Dog

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The Geotech S13 is the shortperiod standard seismometer that contributed significantly to the main achievements of classical seismology. More than 4500 S13-sensors are trembling since more than three decades on behalf of earth sciences for monitoring and research purposes. Besides a impeccable mechanical manufacturing, the 5 kg mass makes the S13 insensitive for thermal noise and convective currents inside the housing.

The invention of the broadband-seismometer terminated the strict distinction between short-period and long-period instruments and let become not only the S13 seismometer often disused.

Therefore we decided to prescribe a rejuvenation cure to this old 'dog'. The high generator constant allows to apply a strong overdamping of the electronic circuit, a method introduced 1983 by Lippmann and Gebrande.

A Lippmann-style seismometer uses a single-coil velocity-feedback method to extend its transfer function to lower frequencies. Strong seismic signals may saturate the electronics, sometimes leading to signal clipping or producing the characteristic 'whale-shaped' transient. This behavior may be avoided by applying a negative resistor front end, that can be tailored such that it allows the enhanced S13 to work like a strong-motion velocimeter, thus preventing saturation.

Some months after the devastating 2009 L'Aquila earthquake (Mw=6.3), we installed at Onna, in the epicentral, area a triplet of extended S13-sensors in a especially constructed seismometer vault. Laboratory simulations and more than 3 years of data allow us to conclude, that new tricks have been succesfully taught to the old dog, called S13.

A Microseism Catalog Based on Broadband Data from the US Transportable Array

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We analyzed and catalogued microseisms recorded in the western United States by Earthscope Transportable Array (TA) broadband stations during the year of 2009. We used eigen-decomposition of spectral matrices to extract power and polarization information for each hour of data recorded at each seismometer. The time- and frequency-dependent results were visualized using spectrograms and geographical animations. Individual microseismic arrivals were identified from array-averaged spectrograms and were cataloged according to several metrics, including initiation time, duration, peak power, average power, dominant period, temporal variation in period (dispersion), degree of polarization, and azimuthal orientation of the polarization ellipsoid. Over 63 distinct microseismic events were identified. The longest duration microseismic signal occurred for more than 250 hours and was associated with the passage of Hurricane Bill in the Atlantic Ocean. The most powerful signal was recorded with a dominant period near 5-sec on December 30, and resulted from wave action associated with an unnamed storm in the North Atlantic Ocean. The seismic observations were compared to excitation predictions computed with the power spectral density of the equivalent pressure generated by the ocean gravity waves using the WAVEWATCH-III ocean wave model. Microseismic excitation predictions were calculated both with and without coastline reflections. Relationships between the microseismic observations and the oceanographic predictions will be presented.

A Ground-Truth Mine Monitoring System

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A Ground Truth Mine Monitoring System (GTMS) is currently being developed under a DOE Phase II SBIR entitled 'Development of Mine Explosions Ground Truth Sensors;. The concept behind the SBIR is to develop an inexpensive, compact seismo/acoustic system that is simple to deploy and can be mailed to an institution for placement near mines that conduct large explosions. The ground-truth data provided by the GTMS can be used to calibrate regional nuclear-explosion monitoring networks. An on-board processor allows for single-station estimation of location, origin time and magnitude (yield) and signal diagnostic parameter data that is transmitted back to a Ground Truth Processing Center (GTPC) via two-way ORBCOMM satellite communications. Two-way satellite communication allows for deployment in remote regions and the possibility of limited waveform transmission that can be used to tune on-board processing parameters. Continuous or event-detected data is kept on two removable flash SD cards of up to 64+ Gbytes each. Low-power consumption allows for autonomous operation using only a 10 watt solar panel and a gel-cell battery. The GTMS has been successfully tested for long-term (> 6 months) remote operations over a wide range of environments including summer in Arizona to winter above 9000' in the mountains of southern Colorado.

On-board processing is being developed that includes detectors, P and acoustic wave phase picking, back azimuth estimation and magnitude (yield) estimates from coda waves and acoustic signals. A specialized leading edge picking algorithm has been developed to remove late bias from STA/LTA picks. A single-station Bayesian location algorithm is being developed that combines prior information on mine location with P and acoustic wave arrival time picks and P-wave back azimuth. A matched filter has been developed to obtain explosion yield estimates from automated impulse per unit area measurements.

Emergence of Continuously Recording Very Large Array Capabilities in Seismology

Oral Session · Wednesday · 2:15 PM · 30 April · Room 7/8
Session Chairs: Rick Aster and James Gridley

Back-Projection Imaging of Aftershocks Recorded by the Dense AIDA Array After the 2011 Virginia Earthquake

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Aftershock Imaging with Dense Arrays (AIDA) recorded 12 days of seismic data following the 23 August 2011 magnitude 5.8 earthquake in central Virginia. AIDA utilized short-period, vertical-component seismographs at 201 locations at 200–400 m spacing to drastically reduce spatial aliasing as compared to traditional aftershock networks. Inter-station correlation enabled a visible detection threshold between magnitude −1.5 and −2.

Traditional local earthquake tomography with ~1 km resolution revealed a homogeneous seismic velocity of Vp = 6.2 km/s and Vs = 3.6 km/s in the aftershock zone. This is consistent with the aftershocks occurring within a single crystalline-rock terrane. Hypocenters were located with an absolute accuracy of ~100 m without using double difference or cross-correlation methods. The hypocenters define a zone of seismicity that is >1 km wide, much larger than the hypocenter accuracy, suggesting a new or immature fault zone. The fault zone is weakly concave upwards in depth and along strike.

Reverse time migration was applied to several of the aftershocks to back-project recorded seismic energy to the source. Events as tiny as magnitude −2 and with signal smaller than noise were successfully imaged as point sources with ~200 m resolution. The propagation of energy release as a function of time and space was observed for events from magnitude 2.5 to magnitude 3.7, the largest event recorded. Slip propagated at a high speed and ruptured a relatively long distance for the magnitude, suggesting that new fractures are being created in strong rock under high stress. Synthetic data tests show that resolution was primarily limited by the temporal sampling rate. Improved temporal and spatial sampling are feasible, and would produce images with sharper resolution.

Aftershock Imaging with Dense Arrays (AIDA)

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Large-scale, dense, continuously recording areal arrays are now commonplace in oil and gas exploration. This new technology represents a transformative technology for the imaging and monitoring of deep structure and tectonic processes. Here we illustrate the potential of this technology with results from pilot studies of aftershocks from two eastern U.S. earthquakes: the magnitude Mw 5.8 August 23, 2011, in central Virginia earthquake and the Mw 4.0 October 16, 2012, near Waterboro, Maine. Aftershocks from both were recorded using unusually dense profiles of seismometers in what has been termed an AIDA (Aftershock Imaging with Dense Arrays) deployment. In Virginia, over 200 recorders were set out in the epicentral area at stations spacings of 200m to a) more precisely determine hypocentral locations and source properties of the aftershocks to ultra-low magnitudes, b) more accurately define velocity structure in the aftershock zone, c) image geologic structures in the hypocentral volume using reflection techniques with the aftershocks serving as illumination sources, d) characterize regional propagation characteristics and e) assess the potential of seismic interferometry for subsurface imaging using both body and surface waves from aftershocks and ambient noise. Key results include a) a substantial lowering of the detection threshold for very small events, b) more precise hypocentral locations, c) determination of rupture mechanisms for very small events, d) high resolution 3D imaging of hypocentral volumes by both refraction and reflection methods applied to the aftershocks as sources and 3) imaging of structure using both natural and artificial ambient noise with surface wave and body waves.

Optimal Design of Large-Scale Seismic Array For Earthquake Source Imaging Constrained by Waveform Coherency of USArray

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Waveform coherence across a seismic array is crucial to back-projection (BP) earthquake source imaging. Previous work indicates the waveform coherence decays dramatically with inter-station distance and frequency. However, these studies use time windows with fixed duration, which naturally degrades the coherence at high frequency. Here, we measure the correlation coefficients of teleseismic waveforms recorded at USArray with window lengths proportional to 1/frequency and the same alignment procedure, filtering and window parameters adopted in teleseismic BP for source imaging. We find the coherency is high across the USArray over inter-station distances >10 wavelengths and up to 5 Hz. The coherence of large/shallow earthquakes decays faster with distance than small/deep earthquakes. For the same earthquake, coherence falls slower along the ray-path than across it. We explain these patterns by a finite source effect, including scattering near the source, supported by synthetic tests. Coherence also decreases with frequency, mainly due to the effect of signal to noise ratio. Our results suggest that coherence is not a limiting factor for array design. The optimal design can be thus inferred from classic array processing principles assuming perfect coherency. Aliasing is inversely proportional to station spacing and resolution is proportional to array aperture. BPs of the Tohoku earthquake based on different subsets of USArray show that spacing should be at most twice the actual USArray spacing (~150 km). As robust array processing requires windows much longer than the wave period, the effective temporal resolution is about 10 periods. Since the BP image averages the rupture process within this window, the spatial resolution of the array design does not need to be smaller than the rupture propagation distance over the window duration. This physical resolution limit provides a constraint on the optimal aperture of the array.

The New Wave Gradiometry Technique Applied to USArray

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Wave gradiometry is a new technique utilizing the shape of seismic wave fields captured by USArray transportable stations to determine fundamental wave propagation characteristics. The horizontal and vertical wave displacements, spatial gradients and time derivatives of displacement are linearly linked by two coefficients, which can be used to infer wave slowness, back azimuth, radiation pattern and geometrical spreading. Spatial gradients of the shifted displacement fields are estimated using bi-cubic splines [Beavan and Haines, 2001]. With singular value decomposition, the spatial gradients are then inverted to iteratively solve for the coefficients at each station, which can then be used to infer the wave field parameters described above. Our results show that the average dynamic Rayleigh wave phase velocity ranges from 3.8 to 4.2 km/s for periods from 60–125s, and 3.6 to 4.0 km/s for periods from 25–60s. It's important to note that these results depend not only on the medium but also on the local geometry of the wavefield. To find the structural phase velocity determined only by the properties of the medium, the first and second derivatives of logarithmic amplitude are required, enabling a solution to the Helmholtz equation [Wielandt, 1992]. We show that the two coefficients that we are solving for, using the gradiometry method, correspond to the gradient of logarithmic amplitude and the gradient of phase, respectively. This enables us to estimate pseudo-structural phase velocities through solutions to the Helmholtz equation, assuming that the structure is smoothly inhomogeneous compared to the heterogeneity of the wave field. Furthermore, the density can be estimated by integrating in the direction of wave propagation, using also the first and second derivatives of wavefield phase. Our modification of the wave gradiometry method is now being employed across the USArray to obtain structural parameter estimates in the eastern portion of the U.S.

A Comparison between Seismic Wave Gradiometry and fK Analysis in the Estimation of the Slowness Vector

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Seismic wave gradiometry is a relatively new array processing methodology that can yield information about a wave's slowness and spatial amplitude changes. The principle is to relate the spatial gradients of the wavefield to two coefficients. The first coefficient relates to the vector slowness, and the second coefficient relates to the seismic radiation pattern. It's a new paradigm in seismic array processing in that it's essentially a 'point measurement' of the wavefield. In practice, however, to estimate spatial derivatives we use an array with an aperture of less than ten percent of the seismic wavelength. As with any new methodology the efficacy must be tested against established methods. In this work we compare gradiometry's estimation of the slowness vector to the results obtained from the well-known fK analysis method. Additionally we explore the internal consistency of gradiometry under the plane wave assumption by systematically changing the master station, for the purpose of calculating spatial derivatives. We incorporate the station location uncertainties using a Monte Carlo simulation to resolve a statistically robust estimation of the slowness vector, which in turn we compare to the result obtained from fK analysis.

Long Beach 3D Seismic Survey: Data Mining Continuous Passive Seismic Data

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Use of passive seismic data in the oil and gas industry has been limited to monitoring hydraulic fracturing and induced seismicity. Recent introduction of autonomous-type seismic data recording systems for conventional active-source seismic reflection exploration surveys provide a valuable by-product, if the that data is preserved: a continuous seismic recording from a dense seismic network over the survey area. The dense exploration network can be thought of as a scaled-down version of the global seismic network and techniques developed to study the earth's interior using global earthquake data can be applied to the dense exploration network.

This presentation describes the results of applying various techniques to passive data acquired using an autonomous seismic recording system. A 57 square kilometer survey 3D seismic reflection survey acquired in early 2011 in Long Beach, California, that resulted in six-months of continuous passive seismic data from a static 5,400 receiver seismic network with a nominal station spacing of 110 meters. The seismic sensor used in the survey was a vertical component geophone with a 10 Hz corner frequency. This continuous passive data set was mined for information that adds value to the active source data, as well as other information that would benefit exploration and earthquake-related studies of the study area. Natural seismicity and ambient noise provide the signal used to extract p-wave and shear-wave velocities, anisotropy information and seismic imaging products. Types of analyses include time-lapse ground motion studies, micro-earthquake detection and location, surface wave interferometry, ambient noise correlation for reflection imaging, receiver functions, and teleseismic event amplitude analysis.

Results show that the seismic instrumentation and seismic network design used for the Long Beach survey are suitable for some of the analyses performed, but also suggest that results can be improved with

Body and Surface-Wave Ambient-Noise Seismic Interferometry Across the Salton Sea Geothermal Field, California

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Seismic reflection and refraction data were acquired in southern California as a part of the 2011 Salton Seismic Imaging Project. A dense linear array of 486 seismometers across the Salton Sea Geothermal Field and Brawley Seismic Zone recorded explosive sources plus 135 hours of ambient noise. The line crosses the Imperial Valley along the southern end of the Salton Sea. There are abundant surface and subsurface ambient seismic noise sources near the array, including tectonic and induced earthquakes, geothermal pumping operations, a railroad, two highways, farming operations, and Salton Sea wave action.

These noise sources produced both surface and body waves in interferometric virtual source gathers. However, some of the noise sources also generated strong artifacts. Two highways and a large geothermal plant acted as strong long-duration point sources, producing both virtual source signal and artifacts similar to those produced by cross-correlation of a large impulsive source. This was addressed by correlating only time windows containing the >300 recorded earthquakes.

Strong surface waves were observed at 0.4–8 Hz, despite the use of 4.5 Hz geophones. Surface wave dispersion curves on the alluvial flanks of the valley show velocity of 225–330 m/s in the upper ~600 m. Within the geothermal field in the central valley, the surface wave velocity increases with frequency from 80 to 240 m/s, indicating a low-velocity layer under a high-velocity cap in the upper ~250 m. Body waves are observed up to 35 Hz and 3 km distance on parts of the line. The highest quality virtual source body waves are produced near anthropogenic noise sources. The virtual shot gathers compare well to the twelve explosive shots along the line, but provide additional, smaller virtual shots between the sparser explosions.

Impact of Scattering on the Design of a Network of Arrays for Earthquake Rupture Imaging

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Many Earthquake Early Warning (EEW) systems currently proposed successfully focus on quickly identifying the epicenter of an earthquake, but often underestimate the magnitude, as simple models fail to consider the length, duration, and directivity effects of finite fault rupture. In contrast, a system of multiple small aperture strong motion arrays close to major faults could be employed to backproject energy in real time and track the fault rupture as it progresses. Such methods assume that the direct arrivals from a new rupture subevent can be resolved from the scattered coda of the previous rupture subevents. Although scattered energy may mask later parts of the rupture, its lower waveform coherency may limit its impact on backprojection resolution.

We examine several of the underlying assumptions in these backprojection methods. To confirm that coherency decays quickly enough for the method to be useful for EEW, we analyze data from four different arrays in Southern California. Over 200 small events are used to examine coherency decay after the P-wave arrival. Although other studies have performed a similar analysis of waveform coda, details of this work are unique to the backprojection scheme suggested, such as window length considered, frequencies, station spacing, and emphasis on early coda. We also review numerical and analytic models of crustal scatterers and their effect on an array's coherency, with particular attention paid to the relative contribution of single scattering (which is easier to computationally simulate) and multiple scattering. Finally, since EEW systems rely on speed, it is desirable to use information from the P-waves, but interference with strong energy from S-waves further reduces our ability to resolve the front of the rupture process. We discuss methods and deployment strategies which would overcome this limitation.

'No-Cost' Acquisition of 3D Reflection Imagery of the Continental Basement

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The current generation of continuously recording, 'superchannel' seismic systems that are increasingly being used to collect 3D seismic imaging of the sedimentary cover for oil and gas exploration are by default also collecting 3D seismic information on the deeper crust. Although the data are recorded continuously for reasons of increased productivity, the exploration companies typically only 'harvest' the first few seconds after their controlled sources are triggered to recover reflections from the first few kilometers of the crust. However, the equipment continues to record, potentially collecting later reflection arrivals from deeper structure. However, these deep data are typically treated as leftovers along with the noise between shots. A systematic program to recover these deep data from industry archives could produce the first extensive coverage of true 3D reflection information on the basement beneath the oil basins in which the exploration companies operate. Here I will discuss the practical limitations on the utility of these industry discards, the value of extended correlation for vibroseis data, the impact of simultaneous shooting strategies and the potential of deblending algorithms to recover deep data even when 'overprinted' by successor shots.

Advances in Seismic Imaging and Monitoring of Time-Dependent Variations: Civil Structures, Near-Surface, and Shallow Crustal Scales

Poster Session · Wednesday · 30 April · Cook/Arteaga

Lithospheric Earth Structure of Texas-Gulf of Mexico Margin from Surface Wave Dispersion and Migrated Ps Receiver Functions

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The seismic velocity structure beneath Texas Gulf Coastal Plain (GCP) is imaged by fitting of surface wave dispersion and velocity analysis of Ps receiver functions. The GCP is a portion of an ocean-continental transition zone, or "passive margin", where attempts to model lithospheric earth structure seismically have been rare. Seismic data from a linear array of 22 broadband stations, spaced 16–20 km apart along a ~330-km-long profile across the Texas-Gulf of Mexico passive margin, were employed to construct a coherent image of the crust and uppermost mantle.

A Common Conversion Point (CCP) stacking technique is applied to teleseismic earthquake data to improve the signal-to-noise ratios of receiver functions. Using an incorrect velocity model for time-to-depth migration of a stacked CCP image may produce an inaccurate image of the subsurface, especially in the presence of substantial lateral velocity variations. To find accurate P- and S-velocity models, we first apply a nonlinear modeling technique to fit Rayleigh wave group velocity dispersion curves via Very Fast Simulated Annealing (VFSA), a global optimization method. We use ambient noise cross-correlation to compute Rayleigh wave group velocity dispersion curves. Statistical assessment tools, such as the parameter correlation matrix and the marginal Posterior Probability Density function, are estimated in order to evaluate the constraints that dispersion data place on model parameters.

P Wave Transfer Functions for the Northern Mississippi Embayment: A Different Approach

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We are using the data from broadband stations of the USArray TA and the Northern Embayment Lithospheric Experiment (NELE), to examine the crust and uppermost mantle in the New Madrid Seismic Zone (NMSZ) and the northern Mississippi Embayment by computing three-component P wave transfer functions. Instead of using the standard processing of P-wave radial and vertical components using a single event recorded at a single station, an estimate of the effective source function

of the event is obtained by stacking all vertical components from regional stations outside the embayment. Stacking vertical components from external stations reduce randomly scattered waves and the amplitude of other locally coherent waves, such as the crustal P wave reverberations. This estimate is then used to deconvolve the three component data for stations inside and outside the embayment. Because the embayment is filled with a thick layer of unconsolidated sediments, target P-to-S conversions from the crust-mantle boundary and other major discontinuities within the mantle are disguised by large amplitude near-surface Ps reverberations. We incorporate wavefield downward continuation using propagator matrix theory to remove the near surface reverberations. In order to do the downward continuation correctly, a detailed velocity structure of the sediment under each station is required which we obtain by a grid search algorithm. We are applying this technique to the available data from the existing TA stations in the area to develop a detailed 3D velocity model for the embayment sediments. This 3D velocity model will be used as a starting model for further model refinements using new data from the higher density linear arrays recently deployed for the NELE.

3-D Shear Wave Model Development of the Texas Region Using an Optimization Scheme

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Understanding Earth's tectonic processes requires analyzing the Earth structure. The objective of this work is to expand on a constrained optimization approach for a joint inversion least-squares (LSQ) algorithm to characterize a one-dimensional Earth's structure of Texas with the use of multiple geophysical data sets. In particular, we apply the Multi-Objective Optimization Problem (MOP) Technique to the 1-D inversion and use four geophysical data sets: receiver functions, surface wave dispersion curves, teleseismic body wave times, and gravity measurements to obtain a better shear wave model of Texas. For this research, we will use MOP formulation to generate quasi-3D shear wave models to determine regions of Texas at would have high and low velocities within the mantle. We used the MOP optimization technique to generate 3D imagery of Texas in order to help us to determine the petrophysical nature of the Lithosphere-Asthenosphere Boundary (LAB). Through the development of our quasi-3D models using multiple data sets, we will be able to evaluate and analysis the upper mantle seismic velocity structures in both the vertical and horizontal directions, which will be the key to our understanding of the overall tectonic structure of Texas. For this research, we collected and process seismic data (receiver function, surface wave, body wave travel times) from USArray, a National Science Foundation funded EarthScope project, plus the collection of gravity from other efforts. USArray, which is part of the EarthScope experiment, is a 15-year program to place a dense network of permanent and portable seismographs across the continental United States. The quasi 3-D velocity models generated from the use of the USArray data that we acquired for the Texas region will provide insight into the tectonic history and physical properties of the Earth structure.

Shear Wave Velocity Structure Beneath Haida Gwaii, Canada, in the Vicinity of the 2012 Mw 7.7 Earthquake

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In this study we constrain the S-wave velocity structure beneath Moresby Island, Haida Gwaii, in the vicinity of the 2012 Mw 7.7 earthquake (Canada's second largest instrumentally recorded earthquake). We utilise data from two existing Canadian National Seismograph Network stations (DIB and MOBC) and take advantage of four additional 3-component seismic stations deployed to monitor aftershock activity of the 2012 earthquake.

It has long been known that there is an element of convergence between the Pacific and North American plates along the primarily strike-slip margin in the vicinity of Haida Gwaii. The M 7.7 earthquake of 2012 was not associated with the strike-slip Queen Charlotte Fault, but rather with a blind thrust fault just to the west of Moresby Island. It was the largest thrust event ever recorded in this region. Previous studies have provided evidence for a subducting slab beneath the northern part of Moresby Island. Our research focusses on new data from seismic stations on central and southern Moresby Island and we look for evidence of subduction along this margin.

In this study we utilise receiver function analysis (time-domain deconvolution) combined with a Bayesian inversion technique to better constrain uncertainties and the likelihood, and nature of interfaces. At each station across Moresby Island, two key features are identified:

1. A continental Moho at 15–20 km depth,
2. A significant low S-wave velocity zone at depths ranging from 25 km to 40 km, generally increasing eastward beneath Haida Gwaii.

These results are consistent with a subducting oceanic plate beneath Haida Gwaii and represent the first evidence that the oceanic plate extends beneath all (or the majority) of Moresby Island. This new model will have applications to earthquake hazard evaluation across Haida Gwaii and further south along this margin.

3D Seismic Reflection Imaging Using Aftershocks of the 2011 Central Virginia Earthquake as Illumination Sources

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One of the primary goals of the AIDA Virginia seismic recording experiment was to evaluate the feasibility of using aftershocks for detailed reflection imaging of geologic structure within the hypocentral volume. In this study we demonstrate how earthquakes recorded by a dense surface array can be used to image the surrounding volume by the application of Vertical Seismic Profiling (VSP) imaging techniques, in particular a variant known as reverse VSP (rVSP). rVSP processing of individual earthquake recordings map the more prominent reflection interfaces beneath the surface profile. The strongest of these reflectors is a planar interface at a depth of approximately 6 to 8 km that directly underlies and is continuous beneath the more steeply dipping aftershock zone. We interpret this event as part of an east-dipping thrust sequence associated with Paleozoic convergence during the Appalachian orogeny. Its continuity suggests that the fault that hosted the Virginia event either does not penetrate to great depth, or has no previous history of significant accumulated offset. It certainly is not consistent with reactivation of a major pre-existing fault. Our current work focuses on producing a more complete 3D imaging by rVSP to CRP transforming and stacking of multiple earthquakes, both to fill out the 3D image space and to increase the signal to noise ratio of weaker reflections. The primary challenges in such imaging are the uncertainties in the location and timing of the aftershocks. A preliminary 3D image generated by rVSP processing of 81 aftershocks shows coherent reflectors throughout the 3D seismic volume.

Group Velocity Tomography for Eastern Mexico and Isthmus of Tehuantepec

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We combine data from noise cross correlations and regional earthquakes recorded by two dense portable arrays and the Mexican National Seismological network to obtain Rayleigh wave tomographic images at periods between 5 and 50 s for central and southeast of Mexico.

Resolution tests show that we are able to recover information over areas $>15 \times 15$ km in the better-covered areas.

At short periods (<15s) the images show good correlation with the shallowest geological features. Low velocity anomalies are related with sedimentary basins and Cenozoic volcanic areas, while high velocities anomalies correlate with the forearc region. A very clear low-velocity anomaly is observed at the north of the Isthmus of Tehuantepec where an active volcanic field is located.

At larger periods (>25s) a low velocity region coincides with the border of the Trans Mexican Volcanic Belt suggesting the presence of a mantle wedge. For these periods high velocity anomalies are related with the shallow presence of the oceanic mantle in the forearc and the presence a shallower mantle in the backarc where the continental crust become thin.

Ambient Noise Tomography of the Katmai Volcanic Complex, Alaska

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This study refines the 3-D S-wave velocity structure in the region of the Katmai Volcanic Cluster through an inversion of ambient seismic noise data. We combine continuous data from the Alaska Volcano Observatory's (AVO) 20 station permanent network with data from a dense 11 station temporary array run from 2008–2009 by the University of Wisconsin-Madison and AVO. The combined data set builds on the work of Thurber et al. (2012), which used only the permanent array data. Data for the period from July to December 2008 is cross-correlated in hour-long segments, then stacked over the entire time period. The continuous data will also be analyzed using phase-weighted stacking in an attempt to improve the Green's functions. Extracted Green's functions are evaluated for quality and the best results are used in a 2-D inversion for group velocity maps at multiple frequencies focused between 0.2 -- 0.7 Hz. The group velocity maps are then used in cell by cell inversions of the 'local' dispersion curves for 1-D Vs structure, which are then assembled into a 3-D Vs model. Checkerboard tests show good model resolution for anomalies greater than 5 by 5 km in size to a depth of ~8 km, suggesting that our ability to resolve anomalous structures should be very good. Preliminary results show anomalously low S-wave velocity in the region of Katmai Pass that could indicate magma storage or a shallow hydrothermal system.

The optimal group velocity maps will be combined with body-wave arrival time data in a joint inversion for 3-D P- and S-wave velocity structure. The relative contributions of the two data types in the joint inversion are controlled by a weighting factor, with the optimal point defined by a trade-off curve. These results should improve the Vs model by combining constraints from both the body-wave arrivals and ambient noise group velocity maps.

Shear-Wave Quality Factor Qs Profiling using Seismic Noise Data from Microarrays

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The assessment of the shear-wave velocity (Vs) and the quality factor (Qs) profiles below a site is necessary to characterize its site response. Recently, methods based on the analysis of seismic noise have proved to be very efficient for providing a sufficiently accurate estimation of the Vs versus depth at reasonable costs for engineering seismology purposes. In this study, first it is investigated if the same methods can also provide, with just a few additional calculation steps, realistic Qs versus depth estimates. A data set of seismic noise collected at the Tito test site in southern Italy by a microarray of seismological stations (with maximum aperture of few tens of meters) was used, and the obtained Qs results are compared with those estimated by independent geophysical investigations. It is shown that the values are consistent and that the seismic noise analysis has the potential to also provide a more comprehensive (Vs and Qs from an engineering seismology point of view) description of the shallow geological structure below a site at low cost. The technique is further applied to data collected by other microrrays in Turkey and Kyrgyzstan. An empirical relationship between the estimated Qs and Vs values is investigated.

Extracting Site Characteristics at Delaney Park Geotechnical Array in Anchorage, Alaska Using Seismic Interferometry

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Seismic interferometry, based on deconvolution of wave motions recorded at various borehole depths, is used to extract the site characteristics including wave attenuation, predominant frequencies, shear modulus and shear-wave velocity profile of a densely instrumented geotechnical array at Delaney Park in Anchorage, Alaska. Surface and six borehole (up to 61 m depth) three-component sensors recorded ten earthquakes having moment magnitude between 4.5 and 5.4 at epicentral distances of 11 to 162 km. Deconvolution of the waveforms recorded at various depths on horizontal sensors with respect to the corresponding waveform recorded at the surface provides upward (incident) and downward (reflected) travelling waves within the soil layers. The simplicity and similarity of the deconvolved waveforms from different earthquakes suggest that a one-dimensional shear velocity model is sufficiently accurate to represent the site characteristics. The travel times evaluated by deconvolution agree with the results obtained by the geophysical measurements of shear-wave velocity at the site. It is also shown that the deconvolution method is effective in computing amplification property of shallow soil layers. The estimated parameters are used for soil-structure interaction modeling of a densely instrumented 20-story steel framed Atwood building, located 166 m from the Delaney Park geotechnical array.

Site Characterization for Marine Earthquake Engineering via Modeling of Ocean-Bottom-Seismometer Observations of Rayleigh Waves and Microtremors

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Shallow shear-wave velocity structure of the top tens to hundreds of meters is essential for site characterization. On land, both active and passive methods are used to determine subsurface velocity structures. With the increasing of ocean industry engineering (e.g., marine platform for petroleum exploitation), shallow shear-wave velocity structure in marine region need to be well investigated. However, it is not a trivial task to study the shallow shear-wave structure in the marine regions. With the ocean-bottom-seismometer (OBS) observations in the Bohai Sea, China, from the year of 2010 and 2011, high quality waveforms of short-period Rayleigh wave are obtained with air-gun source at close to large offset (from 200 m to >6000 m). The dense spacing of air-gun sources (~200 m) and high signal-to-noise Rayleigh waves provide a feasible way to investigate the shallow-shear wave structure beneath the OBS observation lines. Moreover, the horizontal-to-vertical (H/V) spectrums are calculated with the microtremors recorded by the OBS, which is also used to estimate the shear-wave velocity structure beneath the OBS. Shear-wave velocities of 120~220 m/s are obtained from both dispersion curves of Rayleigh waves within 1~5 Hz and H/V spectrum ratio. Our study suggests that HV method is also applicable in marine regions.

A Wave Gradiometry Application in Engineering Seismology: Field Measurement of Nonlinear Soil Behavior in the Near Surface

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Nonlinear soil behavior can be illustrated by a shear modulus reduction curve where shear modulus is decreased as shear strain increased. We develop the reduction curve from field experiment using a seismic shaker truck in order to induce nonlinear soil behavior in the near surface. An array of experimental three component micro-electro-mechanical-system (MEMS)-based accelerometers is deployed to record strong ground motion produced by the shaker truck. Fifteen accelerometers are configured into a two-dimensional gradiometer array consisting of three-by-five array elements configured in a vertical plane. The accelerometers are installed as close as 1.0 m from the shaker truck in several 2-in boreholes at three different depths at approximately 0.5 m, 1.0 m, and 1.5 m, with a borehole spacing interval of approximately 0.5 m. We record a series of strong ground motion waveforms generated by the shaker truck with frequency range from 5 to 40 Hz and different driving-force amplitudes. We use wave gradiometry to solve for phase velocity at each frequency and plot it as a Rayleigh-wave dispersion curve. We observe that the phase velocities decrease with increasing wave amplitude and, hence, the shear moduli decrease as well. Using the recorded seismograms and the position of the accelerometers, we calculate the displacement gradient using a linear inversion method. Monte Carlo error propagation is used to calculate a 95% confidence limit in order to estimate uncertainties in each displacement gradient. By using the two-dimensional configuration in the vertical plane, we can calculate displacement gradient in both vertical and horizontal directions and avoid assuming that the vertical displacement gradient to be of the same order of magnitude as the horizontal displacement gradient. Shear strains produced by the propagating strong ground motions can be up to 6.5 × 10e-5, with a shear modulus degradation of 55%.

Sediment Shear Velocity and Thickness from Seafloor Compliance using Microseisms Noises

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Seafloor compliance is the transfer function between the vertical displacement and pressure as a function of frequency. Seafloor compliance reflects the deformation

of seafloor under ocean wave pressures and is sensitive to the subsurface elastic properties, especially shear modulus, therefore can be used to determine shear velocity of marine sediments. Instead of using long-period infragravity waves as in previous seafloor compliance studies, we investigate seafloor compliance calculated using microseism noise (0.08 - 0.2 Hz). We compare compliances from microseism noises and Scholte waves (a surface wave propagates at a liquid-solid interface), and show that they are identical at microseism band. Using surface wave mode method we calculate synthetic seafloor compliance and examine its sensitivity to water depth, shear wave speed and thickness of sediments. Finally, we invert seafloor compliance observed at 23 deep water Ocean Bottom Seismometers deployed by Cascadia Initiative for sediment thickness and shear wave speed beneath them. Although there is trade-off between shear wave speed and thickness, our method can robustly estimate the travel time delay caused by sediments for each station.

Instantaneous Monitoring of Soil and Structure Dynamics using Autocorrelation Functions Computed with the Stockwell Transform

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Monitoring the speed changes of a medium is very important in detecting variations related to the stress, temperature and fluid content. There are several techniques to do so, and one of them is the use of autocorrelation functions (ACF) that recover a zero-offset reflection seismogram. Traditionally, the autocorrelation functions are computed by stacking several time-windows of seismic data in order to enhance the signal-to-noise ratio. In this sense, the computed ACF shows an average of the dynamics of the physical process. To overcome this limitation, we propose to use the Stockwell transform, which is a time-frequency decomposition of a signal that preserves the phase information, to follow the evolution in time of the spectral properties of a seismic record. More specifically, at each time step, the Stockwell transform provides the amplitude and phase of the instantaneous wavelet that composes the signal, so that an instantaneous ACF can be computed. The analysis of these multiple ACFs allow to compute the time shift at a given ACF produced by the dynamics of the media. Changes of the time shift can easily be transformed into speed changes of the media. In this study, we present preliminary results on the analysis of K-net records that show liquefaction during the Tohoku-Oki 2011 earthquake. Furthermore, we show the effect of moderate to strong events of the response of the Factor building in UCLA, California.

Monitoring a Building using Deconvolution Interferometry from Earthquake and Ambient-Noise Data

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With deconvolution interferometry, we can extract a building response, and hence estimate velocity of the wave that propagates inside the building and the intrinsic attenuation of the building. We apply deconvolution interferometry to earthquake and ambient-noise data recorded inside a building, which is in the Fukushima, Japan. For deconvolution interferometry, we deconvolve the wavefields recorded at all levels with the waves recorded at a target receiver. This receiver behaves as a virtual source, and we retrieve the response of a cut-off building, a short building which is cut off at the virtual source. Because the cut-off building is independent from the structure below the virtual source, the technique might be useful for estimating local structure and local damage. We apply deconvolution interferometry to 17 earthquakes recorded during two weeks and estimate time-lapse changes in velocity and normal-mode frequency. We compute the velocities from both traveling waves and the fundamental mode using coda-wave interferometry. These velocities have a negative correlation with the maximum acceleration of the observed earthquake records. We also apply interferometry to ambient noise, recorded during the same time period in the same building as the earthquake data, and estimate velocities of traveling waves. The velocities estimated from ambient noise are more stable than those computed from earthquake data. Since the acceleration of the observed earthquake records varies depending on the strength of the earthquakes and the distance from the hypocenter, the velocities estimated from earthquake data vary because of the nonlinear response of the building. From ambient noise, we extract the wave velocity due to the linear response of the building.

Dynamic Response Characterization of a Highway Bridge using Ambient Vibrations

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We study the dynamic response of a large-scale highway bridge crossing the Caronte channel (Southern France) using ambient vibrations. The structure is composed of two concrete decks and a metallic one (at the central part) supported by concrete piles of more than 40 m height. We analyze the recordings using frequency (modal analysis) and time domain approaches in order to evaluate the complementary contributions of each methodology. The dynamic response is characterized by normal modes determination, velocities of traveling waves and intrinsic attenuation. Comparison with previous modeling results is done to check some hypothesis of the numerical computations performed beforehand. Additionally, we give special interest to the soil-structure interaction as ambient noise measurements at the base of the structure have also been done simultaneously with the ones on the piles and deck. Since the engineering structure under study is being seismically reinforced, the potential variations of the dynamic response will be evaluated in the near future.

Application of Instantaneous Phase Methods for Improved Noise-Correlation-Derived Dispersion Measurements from a Local Seismic Array

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We investigate the use of instantaneous phase methods for improving the signal-to-noise ratio (SNR) of higher frequency ($f>0.2$ Hz) ambient seismic noise correlations from a local-scale ($\sim$15 km aperture) seismic array. Previous work (e.g., Schimmel et al., 2010; Gaudot et al., 2013) has demonstrated improved SNR in noise correlations generated by using the instantaneous phase for calculating cross-correlations and for selecting and weighting time-window correlations for stacking. We apply these techniques to vertical-component seismic data from a five-week duration deployment of broadband seismographs in the Reno-Sparks, NV region to discern whether phase-based methods permit improved SNR. We are particularly interested in obtaining dispersion measurements from higher frequency ($f>0.2$ Hz) surface waves in order to better characterize the shallow shear-wave velocity of the region. Because of the short duration of the deployment, the resulting vertical-vertical cross-correlations calculated with standard techniques have low SNRs and the corresponding surface wave speed dispersion curves have large uncertainties. We compare the cross correlations computed by standard methods with those computed using two instantaneous phase methods: (1) use of instantaneous phase for the cross-correlations and (2) use of instantaneous phase of the resulting cross correlations to select and weight time series for stacking. Preliminary results indicate improved SNR in the noise correlations made using instantaneous phase methods. These methods may permit improved measurement of inter-station group speeds, such as those made by Noriega et al. (2013), as well as phase speeds.

Reliable Estimation of Shear-Wave Velocity Profile by Inverting Phase Velocity Dispersion Curve and Waveform Comparison

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Rayleigh waves phase velocity dispersion curves are widely used to determine shallow shear-wave velocity profiles in the context of geotechnical, earthquake engineering, and seismic hazard applications. A significant problem with the inversion of phase velocities is its intrinsic non-uniqueness, and although this problem is widely acknowledged, there have not been systematic efforts to overcome the pervasive uncertainty that affects the inverted velocity profiles. Hosseini et al. (2012) was able to reduce the uncertainty associated with the surface-wave inversion using time-domain synthetics on a hypothetical problem. In this study, we apply their procedure to actual data recorded in the field using the Multi-channel Analysis of Surface Waves (MASW) method. A total of 72 vertical geophones with 3 ft spacing were used to record the waves generated using a hammer source. The inversion of the actual dispersion curves yields multiple different velocity models with essentially the same theoretical dispersion curves, which means that there is no objective way to discriminate between the different models. On the other hand, the corresponding time-domain synthetic traces have significant differences, which allows choosing the most appropriate velocity model. Here we assess the usefulness and the limitations of this technique and validate the inversion results with the velocity profile from a downhole seismic survey. Our results show that the use of synthetic seismograms makes it possible to constrain the velocities determined by inversion of Rayleigh wave phase velocities.

Monitoring Pre-Earthquake Activity by Analysis of Ambient Seismic Noise - Encouraging Results

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A significant fraction of the ambient short-period seismic noise at a given site may be attributed to P, S, Rayleigh and Love waves with spectral characteristics strongly dependent on the geological structure underlying the recording station. Unlike an underground nuclear explosion, an earthquake may have intense pre-event activity within the hypocentral region. This pre-earthquake activity, originating several hours or more, not only alters the geological environment within the hypocentral region but also generate new sources of P and SV and SH waves, a fraction of which travel upwards towards the recording station and contribute to the observed seismic noise. We analyzed pre-earthquake seismic noise, recorded by three-component instruments at an epicentral distance of 36 km from a Magnitude 6 earthquake in Nevada. Two distinct premonitory changes in the spectral characteristics of noise were observed: (1) Gradual shift of peak frequencies to lower values, perhaps due to both a decrease in medium velocity and an increase in spatial attenuation due to pre-earthquake activity such as fracturing of rocks; (2) Significant differences in the low-frequency spectral characteristics of the two horizontal (transverse, T and radial, R) and vertical, V components of ground motion. As the origin time of the earthquake approached, a fairly steady increase in the spectral ratios T/R and T/V occurred. A likely explanation is that SH waves trapped within the uppermost low velocity layer can retain relatively larger amplitudes than P and SV, both of which constantly lose energy by conversion to other waves whenever an interface is encountered. The observed spectral peak frequency values were found to be in remarkably good agreement with the theoretical value for SH-wave resonance in this region. These encouraging results suggest an entirely new methodology for obtaining advance warning of a few hours or more of a large impending earthquake, at least in some regions of the world.

Cold Climate Installation Techniques and Instrumentation Developments for Temporary and Long-Term Networks

Poster Session · Wednesday · 30 April · Cook/Arteaga

The Seismic Noise Environment of the Antarctic and the Influence of Instrumentation Techniques

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Recent instrumentation development has opened up even the most remote Polar Regions to year-round, continuous seismographic deployments. Early multi-year networks deployed at high latitudes have illuminated novel seismic signals and noise environments. This noise environment is influenced by, in some cases, new oceanic sources and other processes. However, a handful of sites have experienced unwanted instrumentation and site-induced noise generated in these harsh environments. We analyze recently collected, broadband data from temporary and permanent Antarctic stations to quantitatively assess background seismic noise levels across the continent between 2007–2012, including substantial previously unsampled sections of the continental interior. We characterize three-component noise levels between 0.15–150 s using probability distribution function-derived metrics of power spectral densities and analyze seismic noise levels in multiple frequency bands to examine different noise sources. These metrics reveal patterns of significant seasonal and geographic noise variations across the continent, including the strong effects of seasonal sea ice variation on the microseism, at a new level of resolution. Additionally, we examine the influence of different siting techniques (e.g., ice vaults vs. rock sites) on the seismic noise environment. We include comparisons of the collocated ice cap borehole (146 m and 255 m depth) and surface seismometer installations at South Pole (QSPA) to quantitatively assess noise reductions attained through borehole emplacement. Thorough analysis of the seismic noise environment and its relation to instrumentation and siting techniques in the Polar Regions facilitates optimization of deployments for future seismological deployments in the Arctic and Antarctic regions as well as mountain glacier environments.

Seismic Noise Analyses and Event Quality Assessment for EarthScope Transportable Array Stations in Alaska

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Extensive preparation for the deployment of the National Science Foundation-EarthScope USArray Transportable Array (TA) to Alaska has included developing new methods of seismometer emplacement. The challenging field conditions in Alaska necessitate sensor emplacement strategies that will allow installation in diverse environments, with a smaller, lighter suite of station equipment, while maximizing data quality. IRIS has installed several test stations in Alaska, in various configurations and field settings. These installations have focused on using posthole-style emplacements, in small-diameter augered holes four to ten meters deep that penetrate beneath the active layer of the permafrost, or are cored one to two meters into surface bedrock.

The test stations have now experienced multiple seasonal transitions and we are able to make comparisons with the well-established performance of over 1700 TA stations operated in the lower-48. Sensor performance has been assessed quantitatively using probability density functions summed from power spectral density estimates, which are calculated for the continuous time series of seismic data recorded for each channel of the seismometer. We use these analyses to assess and compare individual seismometer performance for specific frequencies of interest over time. We also examine waveforms of local and teleseismic earthquakes and perform basic seismic analyses (e.g. receiver function calculations) for adjacent stations of different design, to demonstrate the benefits of decreased station noise levels from a scientific standpoint. Results are compared between TA stations in Alaska and adjacent Canada, as well as other relevant regional seismic stations and the lower-48 TA. Our results show that the performance of seismometers using auger- or core-hole installations are at least comparable to the average performance of lower-48 TA stations, and in some cases approach the noise levels of the quietest stations in North America.

Development of New Seismological Instrumentation for Ice Covered Environments

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Ice Covered regions comprise >10% of Earth's continental area; and include regions with poorly understood ice dynamics, tectonic histories, and ongoing geological processes. Scientific investigations of these regions are challenged by extreme weather, limited and expensive logistics, and the physical conditions of the ice environment. We report on the ongoing development of a new NSF MRI-supported community seismic capability for studying ice-covered regions – the Geophysical Earth Observatory for Ice Covered Environments (GEOICE). This project is fundamentally motivated by the need to optimize the collection of high-quality data relevant to key solid Earth and cryosphere science questions. The instrument capability will included: 1) a hybrid seismograph pool of broadband and intermediate elements, for observation of both long-period (e.g., long-period surface waves and slow sources), and intermediate-to-short-period (e.g., teleseismic body waves local seismicity, impulsive or extended glaciogenic signals). The GEOICE instrument, and its power and other ancillary systems, will be specifically designed to both withstand conditions associated with icy environments, including cold/wet conditions and high-latitude solar limitations, and to incur minimal installation time and logistical load (i.e., size and weight), while maximizing ease-of-use in the field, in data handling, and in telemetry compatibility. Key features will include an 'all in one', post-hole-compatible design that integrates the seismometer and data logger into a single environmentally and mechanically robust housing, very low power requirements (~0.2 W) for the intermediate-band seismographs, and advanced power/battery systems that optimize battery capacity and operational limits. The envisioned ~125 element GEOICE instruments will be maintained and supported at the PASSCAL Instrument Center to ensure full and flexible peer-reviewed community use.

Running Real-Time, Year-Round Seismic Stations Across the Greenland Ice Sheet

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Advances in the design and build of very low-power and cold-tolerant seismic and communication instruments have led to a larger presence of seismic stations in the polar regions. Presented here is an update of the technology and methodology that allows the year-round-operation of PASSCAL-monitored stations in the GLISN project. Station designs pioneered at PASSCAL in the Polar program have improved the durability and endurance of polar seismic stations. Enclosed systems have been developed to allow for batteries and key electronics to stay inside a vacuum-panel-insulated station enclosure with bulkhead connectors to external cabling, reducing the station installation complexity and isolating the internal instrumentation from the harsh external environment. To address the equipment and battery low-end operating temp limitations (∼-40C) and the limited and costly deep-field transportation resources, the station overall design requires a careful balance between: low power consumption, battery array size, insulation, and power-production capability.

In the past, most seismic telemetry from cold/remote sites has only transmitted limited state of health (SOH) and allowed limited remote command/control of the instruments. Data are recovered by on-site visits every 1–2 years. A new type of Iridium telemetry using existing Xeos modems (RUDICS) was introduced in 2012, and established at 6 seismic stations. This allowed for the 3X/day automated collection of all continuous SOH and 1Hz seismic data. Station-side problems can be deciphered with greater clarity and confidence and sometimes solved remotely and, if this is not possible, allow for a better-prepared field visit. In 2013, after extensive in-house and field-prototype testing, 2 stations were upgraded to pull both 20 and 1Hz data streams in real-time using full time RUDICS. Future plans are to expand the RUDICS real-time to the remaining stations and to begin testing at other high-latitude stations managed by PASSCAL.

The Yukon-Northwest Seismograph Network: Preliminary Results of Direct Burial Posthole Installation for Real-Time Monitoring

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During the summer of 2013 a total of 7 new broadband stations were installed in south-central Yukon and western Northwest Territories. This network is aimed at improving seismic station coverage in this remote area for real-time earthquake monitoring and structural studies. This area encompasses a large part of the northern Canadian Cordillera, known to be one of the most seismically active regions in Canada but remains poorly studied. The network will be in place for 5 years, therefore overlapping temporally with the Transportable Array in Alaska. Site selection was based on key considerations: easy access from the road network, source of AC power (in some cases) and budgetary constraints. Most of the stations (5 out of 7) use mains power due to low solar insolation and uncertainty with snow depth and overall accumulation; the remaining two stations use solar power. The Trillium 120 Posthole broadband seismometer was selected because it is ideally suited to provide quality data with minimal site preparation, for its proven noise reduction performance, elimination of tilt noise induced through the freeze/thaw cycles as well as increased insulation and ground coupling. Direct burial was performed by hand digging down to two feet deep, followed by an additional two to three feet digging using a two-man auger. The sensor was deposited down the hole, partly covered up with sand and manually oriented to north. Early assessment of data quality yielded excellent results, with station noise comparable to the low-noise level of some of the world's best vault stations despite a very simple and low cost installation technique.

The Alaska Volcano Observatory's Experience in Operating Multi-Parametric Real Time Monitoring Systems in Remote and Challenging Environments

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The Alaska Volcano Observatory (AVO), a partnership of the U.S. Geological Survey (USGS), University of Alaska Fairbanks Geophysical Institute (UAFGI), and the Alaska Division of Geologic and Geophysical Surveys (ADGGS), has installed and maintained volcano monitoring networks in Alaska since its formation in 1988. Station distribution spans over 1200 miles, including Cook Inlet, the Alaska Peninsula and the Aleutian islands. Real-time telemetered data streams include short-period and broadband seismic, continuous GPS, infrasound and web cameras from 33 active volcanic centers. These systems are designed to be robust in extreme weather conditions, survive prolonged periods of little to no solar input, and be resistant to mega fauna and volcanic eruption. AVOs permanent monitoring stations are relatively quick to deploy as remote access requires a helicopter and undeveloped landings. We have short period seismic networks that have functioned without maintenance for 10 years, and digital networks that require annual maintenance. Increased power requirements and maintenance cycles of new digital equipment combined with decreasing funding have proven to be the primary challenges the AVO networks face going forward. This presentation will summarize AVOs experience with design elements and instrumentation that function best in Alaskas unique environments.

Development of Seismic Field System for Multi-Year Field Deployment at Poker Flat Research Range, Alaska

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The environment in polar regions poses a challenge for successful seismic deployments. Cold temperatures and lack of winter sunlight are obvious obstacles, but several other problems (such as remoteness and damage-causing animals) must be overcome, as well. We report on our design, installation, and maintenance of a small-aperture seismic array at Poker Flat Research Range, Alaska. Among the system requirements were: 1) Fully telemetered at sample rates exceeding 100 Hz per channel; 2) Controlled remotely for most operations; 3) Shallowly buried in permafrost; 4) Year round operation; and 5) Robust tilt tolerance. Implicit, as always, is that the system must be built within a finite budget. In our poster, we discuss the steps taken to select candidate components, testing of components that met our requirements, and then summarize the advantages and disadvantages of the components used in the final system. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Minimizing Snow Losses for Photovoltaic Systems in High-Latitude Maritime Environments

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The Alaska Earthquake Center operates and maintains a network of seismic monitoring stations throughout Alaska, many of which are remotely located and depend on stand-alone photovoltaic (PV) power systems. These stations must operate on battery power without any significant solar charging for a minimum of five months out of each year. A subset of these stations, located in the Prince William Sound and Yakutat Bay regions, have poor solar charging histories attributable to heavy snow loads. Such snow, often greater than 2 m deep in the spring, can shade and damage PV arrays and is shown to typically persist in significant levels through the peak of the short charging season. A design methodology is presented for off-grid low-power PV systems in high-latitude maritime environments. Regional climatic data are analyzed. Observations and estimates of solar parameters are applied to solar energy models in an effort to identify the criteria by which PV arrays should be oriented and sized to minimize snow losses.

Deciphering the Earthquake and Tsunami History of Subduction Zones

Poster Session · Wednesday · 30 April · Cook/Arteaga

Tsunami Recurrence in the Eastern Aleutian Arc: A Record of 6–14 High Tsunamis in 3400 Years on Chirikof Island, Alaska

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Despite the Aleutian megathrust's role as the source of some of the largest historical earthquakes and tsunamis, the prehistory of its tsunamis is largely unknown west of the rupture zone of the 1964 M9.2 earthquake. Chirikof Island is the closest island to the trench along this part of the eastern Aleutian megathrust, which ruptured during great earthquakes in 1788 and 1938. Records from Russian settlements show

that a >10-m-high tsunami followed the 1788 earthquake and our Chirikof data suggest that the 1938 tsunami may locally have been as high as 10 m.

Stratigraphy in core transects at two boggy tundra sites on the southwest coast of Chirikof shows a less complete tsunami history at the higher site. In a 500-m-long basin 13–15 m above sea level and 400 m from the sea, 2 to 4 of 10 sandy to silty beds in a 5-m-thick sequence of freshwater peat were probably deposited by tsunamis; the base of the sequence dates to 13 ka. The freshwater peat sequence beneath a gently sloping fan, 7–15 m above sea level and 600 m from the sea, contains 20 sandy to silty beds deposited since 3.4 ka; 8 of these beds we consider as probable, and another 6 as possible, tsunami deposits. Although most of the sandy beds have the consistent thicknesses (over distances of 10–270 m), sharp lower contacts, good sorting, and(or) upward fining typical of tsunami deposits, the beds contain freshwater, rather than marine or brackish, diatoms. We hypothesize that tsunamis traveling inland over low dunes and boggy tundra entrained abundant freshwater diatoms. OSL dating of the third youngest tsunami deposit is consistent with its having been deposited by the tsunami in 1788, and with the second youngest deposit being deposited by a tsunami during an upper-plate earthquake in 1880. Although the proportion of upper-plate versus megathrust tsunami deposits on Chirikof is uncertain, this part of the arc probably sent high tsunamis southward every 250–400 years for at least the past 3400 years.

Evidence for High Tsunamis in the Fox Islands Implies Repeated Aleutian Megathrust Earthquakes in the Unalaska Seismic Gap

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The 1957 (Mw 8.6) Andreanof Islands earthquake generated a destructive, Pacific-wide tsunami and produced a 1200-km-long aftershock zone along the central Aleutian megathrust. Although the source parameters of the 1957 earthquake remain uncertain, tsunami waveform inversions show most slip occurred in the western part of the aftershock zone with little or no slip in the eastern part near Unalaska in the Fox Islands (Johnson and Satake, 1993). This slip distribution model led to the hypothesis that the Unalaska area is a seismic gap. Here we challenge this theory with findings from Sedanka and Umnak Islands where we investigated evidence for high tsunamis at two bays facing the Aleutian trench in the Unalaska seismic gap.

At Sedanka, the youngest of 6 sand sheets underlies drift logs at elevations up to 18.5 m above sea level (asl) and was probably deposited in 1957 based on Cs-137 activity above and below the sand. All 6 sand layers were deposited after ~1.6 ka and exhibit sedimentary characteristics similar to the features of modern tsunami deposits.

At Umnak, in a coastal valley ringed by drift logs stranded up to 23 m asl, we mapped 9 sand sheets with characteristics similar to deposits at Sedanka. Preliminary C-14 analyses limit the maximum age of the oldest sand sheet to ~2.2 ka.

To test the Unalaska seismic gap hypothesis, we compare deposit characteristics at both sites, including thickness, landward extent, runup elevation, grading, bedding, and age. We infer that the highest drift logs at both sites mark minimum tsunami runup in 1957, which implies substantial slip on the megathrust in the Unalaska gap, or extensive offshore landslides at both sites. Evidence for repeated high tsunamis casts doubt on landslides as the primary tsunami source. Instead, our data imply repeated megathrust earthquakes in the Unalaska seismic gap that recur every 280–325 years, and call for a reassessment of Aleutian tsunami hazards to Pacific coasts, especially in Hawaii.

Using Tsunami Deposits to Inform Modeling of Potential Tsunamigenic Earthquake Rupture Zones Near Unalaska Island, Aleutian Islands

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In regions with little seismic data and short historical records of earthquakes, preserved tsunami deposits and tsunami modeling can be used to infer if, when, and where tsunamigenic earthquakes have occurred. Details of these earthquakes, such as magnitude and slip distribution are more difficult to estimate, but are also very important to furthering earthquake and tsunami hazard assessments. The Aleutian-Alaska subduction zone in the region offshore of Unalaska Island is one such region where the historical and paleo-seismicity is poorly resolved. This section of the subduction zone is not thought to have ruptured historically in a great earthquake, leading some to designate the region as a seismic gap. By modeling various historical and synthetic earthquake sources, we investigate whether or not tsunamis that left deposits near Unalaska Island were generated by earthquakes rupturing the Unalaska Gap. Field investigations at Stardust Bay on Sedanka Island (near the eastern end of Unalaska) identified a sequence of six paleotsunami deposits over the last 1770 years that inundated up to 18.5 m above sealevel. We use GeoCLAW and Delft3D to model tsunami inundation from historical and synthetic earthquake sources. Initial results indicate that the previously published sources of the 1957 earthquake cannot account for the tsunami deposit runup observed at Stardust Bay. Modeled inundation from a variety of synthetic earthquakes suggest that the entire width of the Unalaska Gap must rupture with at least 18 meters of uniform slip to generate a tsunami that matches deposit runup. Further modeling of hypothetical sources will explore the effects of using more realistic slip distributions and fault geometries on modeled tsunami inundation for Stardust Bay. We will also attempt to determine relative tsunami magnitudes for each tsunami deposit observed in Stardust Bay, using a forward sediment transport model coupled with the inundation models currently being used.

Unrevealing the History of Earthquakes and Tsunamis of the Mexican Subduction Zone

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The great earthquakes and tsunamis of the last decades in Sumatra, Chile, and Japan remind us of the need for expanding the record of history of such catastrophic events. It can't be argued that even countries with extensive historical documents and tsunami sand deposits still have unsolved questions on the frequency of them, and the variables that control them along subduction zones. We present here preliminary results of a combined approach using historical archives and multiple proxies of the sedimentary record to unrevealing the history of possible great earthquakes and their tsunamis on the Mexican Subduction zone. The Mexican subduction zone extends over 1000 km long and little is known if the entire subduction zone along the Middle American Trench behaves as one enormous unit rather than in segments that rupture at different frequencies and with different strengths (as the short instrumental record shows). We searched on historical archives and earthquake databases to distinguish tsunamigenic events registered from the 16th century to now along the Jalisco-Colima and Guerrero-Oaxaca coastal stretches. The historical data referred are mostly from the 19th century on since the population on the coast was scarce before. We found 21 earthquakes with tsunamigenic potential, and of those 16 with doubtful to definitive accompanying tsunami on the Jalisco-Colima coast and 22 tsunamigenic earthquakes and the Oaxaca-Guerrero coast. Evidence of great earthquakes and their tsunamis from the sedimentary record are scarce, perhaps due poor preservation of tsunami deposits in this tropical environment. Nevertheless, we have found evidence for a number of tsunamigenic events, both historical and prehistorical, 1932 and 1400 AD? in Jalisco, and 3400 BP, 1789 AD, 1979 ad, and 1985 AD in Guerrero-Oaxaca. We continue working and several events are still to be dated. This work would aid in elucidating the history of earthquakes and tsunamis on the Mexican subduction zone.

Development of Next Generation Field Methods for Portable Broadband Seismic Arrays

Poster Session · Wednesday · 30 April · Cook/Arteaga

Crustal Structure of the St. Lawrence Corridor from Montreal to the Charlevoix Seismic Zone from a Temporary Broadband Array

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While many of the most seismically active zones of eastern Canada lie along the St. Lawrence River, the region is not uniformly active. The three primary seismic zones (Charlevoix, West Quebec and Lower St. Lawrence) are separated by regions of very low seismicity. The reasons for the different levels of activity are not well

understood. To determine whether there are physical or structural differences which might explain the difference in activity rates temporary broadband seismometers were installed along the St. Lawrence River in the region from the Charlevoix Seismic Zone, northeast of Quebec City, to Montreal to fill in gaps in broadband coverage by the Canadian National Seismograph Network (CNSN). Stations were typically installed for about two years and then moved to new locations. Thirteen temporary sites as well as the CNSN stations in the region of interest have been evaluated. The crustal structure beneath the stations was modeled using teleseismic receiver function analysis. Preliminary models were obtained using a simple linear inversion. Once the station closed and no new data were forthcoming a Neighborhood Algorithm inversion was performed to provide a more exhaustive search of the model space and a quantitative ranking of the relative fits of the models tested. Regional scale features such as a crustal discontinuity at about 20 km depth and Moho at 35–40 km can be correlated from one station to another. The resulting structural models do not point to any significant difference between the seismic and aseismic regions, suggesting that perhaps the differences are temporal although small scale structural differences cannot be completely ruled out. As the US Transportable Array moves into the study area stations close to the St. Lawrence will be analyzed to further fill in gaps in coverage.

Performance Modeling of the Transportable Array in Alaska: Estimated Magnitude of Completeness and Location Accuracy

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The EarthScope transportable array is planned to begin deployment in Alaska in 2014. Detection of more small events and location of events with improved accuracy will allow for more to be learned from the data collected. Just how well will the transportable array perform? A modeling tool has been developed which allows estimates of seismic array performance to be made in the absence of a catalogue. Existing stations in Alaska, British Columbia and the Yukon Territory were used to generate a site noise field for the region. A simple one-dimensional velocity model was assumed. Projected station locations as of December 2013 were used. Existing station instrumentation was modeled for its contribution to the noise floor, and new stations are assumed to be posthole Trillium 120 seismometers. The effect of several important array configurations are being modeled: a) existing instrumentation b) the proposed transportable array, including new stations in the Yukon c) the proposed transportable array, excluding new stations in the Yukon d) several hypothetical permanent arrays derived from the transportable array by removing all but a fraction of the stations. These comparative analyses show the importance of including the Yukon in the array, and the utility of leaving behind a relatively dense network when the transportable array project is finished. It is proposed that further work be done to validate this modeling by determining the performance of the existing array from the known catalog, and to improve upon the initial velocity model used as the transportable goes into service.

Northern Embayment Lithospheric Experiment (NELE): Summary, Status and Noise Analysis

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NELE is an EarthScope passive array experiment designed to resolve variations in lithospheric structure that illuminate tectonic processes in the northern Mississippi embayment. It is composed of four 6-month deployments of broadband USArray Flex Array and borrowed stations to fill in the Transportable Array grid over a period of two years (September 2011 to October 2013) in 36 locations with sampling frequency of 40 Hz, as well as a two-year deployment (July 2013 to June 2015) of 51 broadband seismometers along three profiles with an average station spacing of 20 km. The stations on the linear profiles are currently recording at a rate of 100 samples per second and are augmented by 37 existing regional broadband network stations. In order to estimate the overall station quality and level of earth noise at each site, we examine the probability density functions of power spectral densities calculated using McNamara and Buland's (2004) method with comparison to the Alburquerque Seismological Laboratory low noise model. Diurnal, weekly and monthly variations in the noise field are useful for establishing the performance of the NELE array, for detecting possible operational problems, and for examining the amplification of the ambient noise field by the thick, low-velocity embayment sediments. Examples of teleseismic and regional earthquake seismograms over the linear profiles demonstrate interesting differences in wave propagation inside and outside of the embayment. (*N. Al Noman, C. Ammon, A. Amosu, S. Ausbrooks, S.T. Bisrat, B. Bockholt, J. Bollwerk, R. Christianson, M. Cooley, D. Dangkua, H. DeShon, M. Dhar, L. Feng, L. Guo, Y. Hao, E. Haug, R. Herrmann, S.P. Horton, M.M. Huda, S. Kelemencky, J. Kutliroff, C.A. LANGSTON, B. Mattingly, C. McGoldrick, J. Meredith, A. Mostafanejad, S.M. Mousavi, C.A. Nyamwandha, P. Ogwari, L.P. Ogweno, C.A. Powell, D. Steiner, W. Thomas, Y. Yang, B. Young)

Analysis of Micro-Earthquakes in the Sierra Madre-Cucamonga Fault Zone Transition as Recorded by a Temporary Seismic Deployment

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The Sierra Madre-Cucamonga fault zone is an active, North-dipping thrust fault system located at the base of the San Gabriel Mountains. Near the mouth of San Antonio Canyon, the fault bends and transitions from the Sierra Madre Fault to the Cucamonga Fault. Coinciding with this bend is the active San Antonio-San Jose fault system. Where the Sierra Madre fault transitions into the Cucamonga fault near the mouth of San Antonio Canyon, it is poorly exposed. Major population centers, including Upland, Rancho Cucamonga, and Claremont, are susceptible to seismic hazards presented by this fault system.

During the summer of 2013, we conducted a micro-seismic survey of the Sierra Madre-Cucamonga fault zone. Nine Guralp CMG-6TD seismometers were deployed in the foothills of the San Gabriel Mountains. At the end of the two-month deployment period, our network had detected over 150 local earthquakes. Included in this catalog are two M3.7 earthquakes that occurred in the Pomona area. This strike-slip faulting doublet is part of a sequence of tens of events that may connect to the Upland earthquakes along the San Jose fault, which is thought to continue through Cal Poly Pomona campus. To better capture this sequence we moved one of our seismometers to a location directly above the doublet.

The waveform data recorded by our network, together with data from the Southern California Seismic Network, will be processed in order to (better) locate these earthquakes. We plan to use a combination of the HYPOINVERSE, VELEST and, eventually, hypoDD software packages to determine absolute and relative earthquake locations. These locations will yield a better understanding of the fault zone geometry and clarify the three-dimensional relationships of the local fault systems.

What Have We Learned from Data from Purpose-Built, Direct-Bury Sensors at Poker Flat, Alaska?

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Optimizing speed and efficiency for deploying temporary seismic stations can greatly reduce logistics costs in remote areas. The IRIS/PASSCAL Instrument Center (PIC) has been exploring methods for emplacing broadband sensors that reduce the time and materials required. Questions remain as to whether these new emplacement techniques produce data of equivalent or better quality than standard temporary seismic vaults. To test the impact of sensor emplacement on data quality, the PIC completed co-located installations in July 2013 at Poker Flat, Alaska, allowing the comparison of data quality and sensor performance from purpose-built direct-bury broadband sensors emplaced in augered holes with observatory-type broadband sensors installed in Transportable Array (TA) and PASSCAL-style temporary vaults. To date, analysis has shown these directly-buried sensors provide similar quality data to that of sensors installed in temporary vaults, while offering the benefits of reduced deployment time, construction material, and logistical requirements. Meeting these criteria is critical to allow Principle Investigators to effectively and efficiently deploy within the future TA Alaska footprint.

Median PSD calculations from the Poker Flat installations, through November 2013, show that the direct-bury installations compare favorably with PASSCAL-style temporary vault installations. Direct-bury installation median PSDs are also comparable to those of the nearby TA vault installation: the horizontal components to periods as long as 10 seconds and the vertical components to beyond 100 seconds. With the additional data collected through Spring 2014, we analyze the performance of direct-bury installations vs. temporary-vault installations using monthly and seasonal PSD PDFs, magnitude-squared coherence, signal-to-noise ratios, and cross-correlation.

A Discussion of Seismic Velocity Models, Attenuation and Stochastic Properties as Indicators of EGS Favorability in Dixie Valley NV

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Seismic attenuation, ambient-noise and signal spectral content and crustal stochastic properties are investigated as indicators of Enhanced Geothermal System (EGS) favorability, as opposed to using seismic velocity models alone. The most important EGS site selection criteria are: temperature greater than 200–250°C at 3–5km depth and rock type (permeability and porosity).

We use a unique database of continuous seismic data collected at 42 three-component broadband station locations in the 2011–2012 in Dixie Valley, NV (DV). In this area, a high resolution P and S seismic velocity model and was previously estimated, using ambient seismic noise and signal interferometry. Green's Functions extracted from autocorrelation and crosscorrelation beams are further analyzed to estimate crustal attenuation and stochastic properties. Preliminary results of seismic velocity model analysis show a slight correlation of high Vp/Vs models with high well temperature gradients. Anomalies in the GF frequency content are observed in the DV geothermal production areas when compared to non-production areas. These results will be statistically compared to the DV EGS favorability map estimated by Altarock Energy Inc.

Diverse Mechanisms of Subduction Zone Fault Slip: Exploring the Relationships Among Seismic Rupture, Transient Slip, and Steady Creep

Poster Session · Wednesday · 30 April · Cook/Arteaga

Temporal Variation of A Large Slow Slip Event at the Southcentral Alaska Subduction Zone During 2009–2013

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We identify and study a Slow Slip Event (SSE) in the southcentral Alaska subduction zone during 2009–2013 using GPS measurements. This is the second large SSE in this region since modern geodetic measurements became available in 1993. This SSE occurs downdip of the main asperity that ruptured in the 1964 Alaska earthquake, on the same part of the subduction interface as the earlier 1998–2001 SSE. The average slip rate of this SSE is ~4–5 cm/yr, with a cumulative moment magnitude of Mw 7.5 through the end of 2012. As an initial study, we divide this SSE into two phases according to their transient displacement time evolution; their slip distributions are similar to each other but slip rates are slightly different. The time and space dependence of the GPS displacements suggest that the slip area remained nearly the same during Phase I, while the slip rate increased with time. The SSEs occur on a transitional section of the subduction plate interface between the fully locked updip part and the freely slipping deeper part. During the 1964 earthquake, slip on the region of the SSE was much lower than slip in the updip region. Based on this observation and the repeated SSEs, we conclude that this part of the interface slips repeatedly in SSEs throughout the interseismic period and does not build up a large slip deficit to be released through large slip in earthquakes. We will also adopt a time-dependent inversion strategy to see the whole picture of this event, investigate its detailed temporal slip variations and discuss how the slip propagates during a long-term large SSE.

Network Matched Filtering as a Tool for Characterizing Seismic Sequences in Alaska

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Plate boundary faults are known to produce a wide range of seismic signals associated with a variety of modes of fault slip. Large earthquakes are the most dominant signals, but aftershock sequences are useful in defining the rupture area as well as tracking postseismic processes (e.g., afterslip). Earthquake swarms, here defined as a temporary increase in seismicity rate without a clear triggering mainshock, are sometimes related to aseismic slip, but their implication for subduction megathrusts is unclear. Non-Volcanic Tremor and swarms of Low Frequency Earthquakes are thought to be related to aseismic slip deeper on subduction megathrust plate interfaces, and are proving to be useful for probing fault behavior and interaction. In order to be useful, each of these types of sequences need to have as complete a catalog of detected events as possible. Here, we utilize a network matched filter (waveform correlation, or template matching) approach to more completely characterize seismic sequences throughout Alaska.

Alaska provides an excellent natural laboratory for developing an automated network matched filter technique, as there are a variety of highly active and diverse seismic regions. There is also a great deal of disparity in station coverage between different regions, with Cook Inlet and several volcanoes having dense coverage but large areas of Southeast Alaska, the Aleutians, and Northern Alaska having extremely sparse coverage. We present results of template matching for various seismic sequences throughout the state. We find that template matching seismic sequences can increase the number of detected events 2–10 fold when used in conjunction with traditional seismic techniques. This allows for more robust statistics of seismic sequences (e.g., b-value) and more detailed tracking of the evolution of seismic sequences and seismicity rate changes. Lastly, we test methods for automated double difference relocation of matched-filter enhanced catalogs.

Potential Causes for Along-Strike Variability of Slow Slip Events in South-Central Alaska

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Slow slip events (SSEs) are observed in subduction zones around the world and exhibit a wide range of recurrence intervals, durations, and spatial extents. A ubiquitous feature of SSEs is the along-strike variability of these characteristics. However the cause and long-term effects of such variability is poorly understood. Additionally, it is unclear whether such variability and segmentation of SSEs persists beyond human time scales. Here we employ the earthquake simulator RSQSim to model a megathrust, which consists of seismogenic, slow slip, and continuous creep sections. The slow slip section is segmented to explore potential causes of along-strike variability in recurrence intervals, durations, and spatial extent, by varying parameters such as the effective normal stress, frictional properties, and slip rates. RSQSim enables simulations of long histories of SSEs over all orders of magnitude, which allows for robust characterization of the effects of variation in parameters. Preliminary results show even small variations in these parameters have a significant effect on observable characteristics of SSEs, which begins to illuminate the primary controls on along-strike variability. For example, a decrease in the effective normal stress from 9MPa to 3MPa results in a decrease in the mean recurrence interval and event duration from 35 to 15 months and 44 to 16 days, respectively, but increases the mean propagation speed from ~7 km/day to ~24 km/day. This research builds on the previous study and considers variations in fault geometry (i.e. tears in the fault) and fault roughness in addition to the parameters discussed above. Ultimately this work aims to reproduce observed SSEs in south-central Alaska.

A Provably Stable Finite-Difference Method for Earthquake Cycle Simulations ithin Subduction Zones

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We are developing a computational method for earthquake cycle simulations within complex geometries. The method is developed for the classical plane-strain problem that can incorporate non-planar fault geometries and material heterogeneities. The off-fault volume is discretized using finite-differences and coordinate transforms to handle the curvilinear grid that conforms to the fault. All boundary conditions are imposed weakly, yielding a provably stable method. As a first step towards developing this method, we consider a planar, vertical strike slip fault governed by rate-and-state friction, and load the system at the remote boundaries at the slow, tectonic plate rate. During the long interseismic period we solve the equations for static-equilibrium. Once an event nucleates we have the option of simulating quasi-dynamic events within the framework, or use the current numerical solution as initial input into the dynamic rupture code SORD that captures the fine details of wave propagation. An important application for this computational method will be to fault geometries representative of subduction zones, where the earthquake cycle may be strongly influenced by both fault geometry and material property variations.

SSE-Related Seismicity on the Northern Hikurangi Subduction Margin, New Zealand

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The subduction interface at the northern Hikurangi subduction margin, New Zealand, experiences a wide diversity of SSEs at depths less than 15 km. In the last two years alone a large shallow (Mw 6.8, <15 km depth) SSE occurred on the subduction thrust beneath Hawke Bay in February 2013, a large shallow (Mw 6.6, <12 km depth) SSE occurred offshore Gisborne in mid-2013, and a moderate (Mw 6.3, <15 km depth) SSE occurred near Mahia peninsula, in October 2013. Since 2011 we have been recording associated seismicity on a temporary broadband seismometer array, with 8 seismometer sites positioned between Mahia peninsula and north Gisborne, the data supplementing the recordings from the national New Zealand GeoNet seismograph network. The array reduces the average seismometer spacing down from ca.25 km to ca.12 km above the Mahia-Gisborne SSEs, and enables higher resolution studies of the seismicity on and near the subduction megathrust, which is located just ca 12 km beneath the seismometer array.

We have observed a wide range of seismic behaviour immediately before and during the SSEs. A shallow SSE in December 2011 was preceded by an intense burst of more than 100 M2-3 events, well located within the subducted Pacific crust below the subsequent SSE, while the February 2013 Hawke Bay SSE, which involved 1.5–2 cm of horizontal displacement on cGPS sites, was accompanied by M3-4.5 events located on the megathrust, between 10-km and 30-km down-dip of the SSE. Matched-filter analysis is now being used to examine smaller events in more detail, in order to track the temporal-spatial movement of this seismic activity. Further analysis of kinematic displacements from 30s and high rate GPS data of the existing GeoNet network is also being undertaken.

Earthquake Triggering Along the Hikurangi Margin: Implications for Fault Strength and Stability

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Earthquake triggering by dynamic stresses serves as a mechanical probe of the strength and stability of faults, because faults must be critically stressed in order to respond to small transient stresses. The Hikurangi margin has one of the highest rates of microseismic triggering of any subduction zone studied to date. The high triggering susceptibility in Hikurangi may be related to the uniquely low coupling in this region, evidenced by episodic slow slip at relatively shallow depths (~15 km). Using a stacking method to pull out subtle triggered rate changes in large populations of micro-seismicity (previously applied to California and Japan) we find that the northern Hikurangi margin responds strongly and systematically to surface waves from remote earthquakes. Spatial variations in the susceptibility to dynamic triggering along the subduction zone are evidence of the differences in strength between seismically coupled and uncoupled portions of the Hikurangi plate margin. The region of highest micro-seismic triggerability corresponds to the mapped location of shallow slow slip events. These two phenomena – microseismic triggering and slow slip – have not previously been observed to coincide. Japan, for example, appears to be at least a factor of 3 less triggerable using the same method, with essentially no triggered micro-seismicity. Further study in this region will help constrain the fault conditions that favor dynamic earthquake triggering and clarify the relationship between fault strength and seismic coupling.

High Resolution Detection and Location of Low Frequency Earthquakes Using Cross-station and Cross-detection Correlation

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Particle-velocity waveforms of low-frequency earthquake (LFE) templates corresponding to near-vertical, source-receiver geometries on Vancouver Island exhibit a dipole wavelet that is characteristic of a moment tensor point-source and shallow thrust mechanisms. Since S-wave energy is strongly excited for this geometry and produces highly similar template waveforms at network stations with consistent polarities on horizontal components, raw LFE waveforms are also likely to have high coherence. As previously proposed by Armbruster, Rubin and co-workers, this coherence favors cross-station approaches for the detection and location of LFEs and tremor. We develop a cross-station correlation approach based on 3 principles: waveform similarity, causality and multi-channel phase consistency. Our LFE location and detection approach comprises three stages. We first use our cross-station algorithm to get detections on the fly, which results in hundreds of individual detections per day during strong tremor with a precision of less than 3 km. Second, we use these detections to construct a catalogue and identify new templates for network correlation detection (Gibbons and Ringdahl 2006, Brown et al. 2008). Third, we perform fine scale relocation by solving for the optimal delay times across hundreds to thousands of independent network detections and across stations, achieving a resolution of a few hundreds of meters. We demonstrate application to separate arrays on Vancouver Island and northern Washington. As previously observed by others (Houston 2011, Rubin 2013), we were able to resolve different modes of LFE propagation: the typical migration along strike to the northwest (about 5–10 km/d) which is consistent with tremor catalogues by Wech and Kao, along strike rapid tremor reversal (RTRs) with velocities in the range of 5–30 km/h and streaks of LFEs migrating roughly downdip or updip with velocities of tens of km per hour.

PBO Strainmeter Measurements of Cascadia Episodic Tremor and Slip Events

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Analysis of the frequency, duration and magnitude of Episodic Tremor and Slip (ETS) events in the Cascadia megathrust subduction zone may provide insight on deformation processes at the slab interface and help define how the amount of strain released during these episodes compares to that released during subduction zone earthquakes. The Plate Boundary Observatory (PBO) currently operates 39 strainmeters in the U.S. Pacific Northwest and on Vancouver Island, Canada. These sites are multi-instrumented; all include 2 Hz geophones and meteorological instrumentation while a subset include tiltmeters and pore pressure sensors. Several are co-located with GPS sites. The strainmeters provide unprecedented temporal resolution of the ETS events as they evolve and migrate along the Cascadia subduction zone. In this presentation we document the ETS events detected by PBO strainmeters since installation of the first sites in 2005 and demonstrate how the signals can be isolated from the sometimes-noisy strainmeter data.

UNAVCO maintains and operates the PBO network, which includes over 1100 GPS and 82 strainmeter sites. For the strainmeter network, UNAVCO generates an Earthscope Level 2 processed strain time-series that have had tides, offsets, instrument strain removed and transformed to obtain areal and shear strains. These data sets are updated automatically every 24 hours and a follow-up data set that has been reviewed by a data engineer is released every 7 to 10 days. For events of special interest UNAVCO generates a 1-sps processed strain time series that also includes tilt data, pore pressure and high-rate meteorological measurements if available. Site information, data quality measurements, current strain plots and strain time-series for all PBO strain instruments can be obtained from the UNAVCO PBO web page (http://pbo.unavco.org/).

Tremor and Seismicity in the Northern Costa Rica Seismogenic Zone Leading up to the September 5, 2012 Earthquake

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On September 5, 2012, a Mw 7.6 earthquake occurred in the Nicoya Peninsula of Costa Rica, the largest earthquake in the area in over 60 years. Large slow slip and tremor events have been recorded on the Nicoya Peninsula approximately every two years, with smaller events, particularly tremor episodes, occurring much more frequently. We identify the locations of tremor and seismicity on the Nicoya Peninsula in the months leading up to and following the September 5, 2012 earthquake. We identify and locate tremor using a combination of visual examination and the automated cross-correlation algorithm modified from Kim et al. (2011) based on the method developed by Wech and Creager (2008). Using these locations we analyze the space-time progression of tremor leading up to a characteristic earthquake on the plate interface below the Nicoya Peninsula. We also compare both tremor and interplate earthquake locations to the well determined distribution of slip in the mainshock to image fault plane heterogeneity in this region.

Comparison of Velocity and Attenuation Patterns along the Frictionally Heterogeneous Nicaragua-Costa Rica Seismogenic Zone

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The Nicaragua/Costa Rica segment of the Middle America subduction zone exhibits properties that are highly variable along strike and down dip. These properties include age, temperature, convergence, hydration, overriding geology, and subducting seamounts/ridges. We use this margin to examine how variable conditions affect earthquake behavior through Vp, Vs, Vp/Vs, and attenuation (Qp) images derived using local earthquake tomography methods. Within the seismogenic zone, we find the margin to be highly variable along strike in Vp/Vs, seismic velocity, and attenuation. Low velocities dominate the Nicaragua region where the plate is thought to be very hydrated. Low velocity amplitudes weaken towards the south in Costa Rica. Microseismicity along the entire plate interface is confined to a low Vp and low Vp/Vs region extending from 30–50 km from the trench to approximately the slab-continental Moho intersection, though there is along-strike variability. In locations with ample resolution, seismogenic zone earthquakes seem to be limited down-dip by a high Vp/Vs at the continental Moho intersection with the subducting slab. This may suggest serpentinization of the mantle wedge. Areas reported to have SSE or LFE are imaged as reduced Vp, Vp/Vs, and highly reduced Qp (high attenuation). Low Vp and Vp/Vs anomalies may suggest moderate overpressures along the plate interface and define the seismogenic zone. Increased Vp and Vp/Vs anomalies updip and downdip of the seismogenic zone may reflect transitions to more extreme overpressures. These conditions may favor slow slip and tremor processes. New Q models will be presented for the margin. We will highlight findings in the Nicoya region, the site of the M7.6 2012 Nicoya event, in the tsunami earthquake region offshore Nicaragua, and in southern Costa Rica near the CRISP drilling site. We compare our results with other geophysical studies including apparent stress, coupling, earthquake rupture, and SSE/NVT occurrence.

Examining Apparent Stress in Microseismicity along the Costa Rican and Southern Nicaragua Segments of the Middle America Trench

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The subduction zone along the Middle America Trench includes significant spatial heterogeneity along the subducting plate as well as a wide range of slip processes, from large earthquakes to slow slip and tremor. An important question is how the spatial heterogeneity affects the types of slip on the plate interface. Along the Nicoya Peninsula, oceanic crust from two different spreading centers is subducting, with the transition from topographically rough in the south to smooth subducting crust in the north; both large earthquakes and slow slip events have also been observed in this area. Subducting Cocos Plate crust formed at the East Pacific Rise (EPR) is smoother and seismicity onset is commonly >20 km depth. Cocos Plate crust formed at the Cocos-Nazca spreading center (CNS) is topographically rough, including the subducting Quepos Plateau, and seismicity onset is shallower than on EPR crust. Slow slip events have been observed updip of seismicity on EPR crust near Nicoya Peninsula, and throughout and downdip of the seismogenic zone on CNS crust under southern Nicoya. GPS observations also suggest variable plate coupling along the Nicoya Peninsula and offshore Nicaragua. To further explore the subduction zone heterogeneity, we determine earthquake apparent stress, a source parameter that can be related to plate coupling, for $\sim$500 events $0.9 \leq M_L \geq 3.9$ from 1999–2006 offshore Costa Rica and southern Nicaragua. We use a spectral ratio technique with amplitudes of the S-wave coda to solve for the seismic moment, corner frequency, and apparent stress. Events are organized into spatial clusters before computing ratios in order to minimize path effects. Preliminary results suggest very heterogeneous apparent stress values of $\sim 0.008 - 2$ MPa, without dependence on event size or depth. The heterogeneity is consistent with earlier work in the area, but current results include lower values of apparent stress than previously determined for the region.

Spatio-Temporal Variations of Afterslip and Aftershocks Reveal the Role of Fluids at the Megathrust Ruptured by the Mw8.8 2010 Maule (Central Chile) Great Earthquake

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Modeling of geodetic and seismologic data at subduction zones suggests that the distribution of frictional properties on the megathrust is highly heterogeneous. It is however unclear whether the spatial location of asperities (stick-slip patches with velocity-weakening frictional behavior) and barriers (stable or conditionally-stable sliding patches with velocity-strengthening frictional behavior) is a permanent feature or it changes from of one great earthquake to the next one. We aim to face this question analyzing the spatio-temporal behavior of aftershocks and afterslip that followed the Mw8.8 2010 Maule earthquake, and comparing this behavior with coseismic slip and preseismic geodetic locking. Afterslip at the megathrust has been computed inverting surface deformation observed by a dense network of continuous GPS stations. We used the NEIC catalog to compute the b-value that characterizes the frequency-magnitude distribution of seismicity. We created maps and time-series for both parameters and performed a novel statistical correlation approach between them, showing that the southern coseismic asperity has low b-values and very small afterslip during the entire observation period suggesting rapid healing and re-locking of a mostly dry fault, whereas for the northern coseismic asperity both parameters fluctuated at high levels during the first months after the earthquakes and then gradually decreased likely indicating the expulsion and/or precipitation of pore fluids at the megathrust. The contrasting postseismic behavior inferred along the strike of this ruptured fault segment only partially resembles the preseismic distribution of fault locking and b-value and the long-term geological structure of the forearc (as inferred from gravity anomalies). This indicates that frictional properties are loosely controlled by this structure and transient processes likely related to the movement of fluids play a primary role in regulating the distribution of fault friction.

Temporal Variations of Intraplate Earthuake Activity Following the 2011 Tohoku-Oki Earthquake

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The locked zone between the subducting and overriding plates host the planet's largest earthquakes, including all of the recorded events of moment magnitude 9.0 or larger, however a significant portion of subduction zone events are intraplate events which occur within the plate, rather than along its boundary. In this study we examine the temporal change of intraplate earthquake activity following the 2011 Mw 9.0 Tohoki-oki earthquake. Due to the large rupture area and displacement of the Mw 9.0 thrust event, we expect that the stress changes within the slab from this event could be comparable in size with those from slab pull and slab bending and consequently that the intermediate depth events directly below the locked region will reflect the change from the slab coupling promoting extensional stresses to compressional stresses. Specifically we expect that earthquake activity in the upper plane of the Tohoku region, which is largely down dip compressional, would be promoted, while the earthquake activity in the lower plane, which is largely down dip extensional would be suppressed, relative to their pre-Tohoku-Oki Earthquake levels. We find that down dip of the 2011 source region the ratio of intraplate earthquake activity in the upper and lower planes of the Tohoku region double seismic zone changes abruptly following the 2011 rupture by a factor of 3 to 5. Capitalizing on insights into the large-scale and long-term behavior of deformation in subduction zones using models of thin sheets we quantify the effect of slab bending on subduction zone seismogenesis. We combine laboratory-based rheological models, precise estimates of slab shape from relocated earthquake hypocenters, estimates of the state of stress in the plate from intraplate focal mechanisms, and response to the 2011 Tohoku-Oki Earthquake to provide constraints and insights for intraplate subduction zone seismogenesis.

Interaction of Trench-Parallel Fault Systems and the Subduction Zone Earthquake Cycle Investigated with the IPOC Creepmeter Array in N-Chile

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To understand the interaction of trench-parallel fault systems with the seismic cycle of the underlying subduction zone, we monitor displacement of the Atacama Fault System in N-Chile with an array of 11 creepmeters. The creepmeters are installed along four different segments of the main fault system, located in the forearc above a 400 km long segment of the Peru-Chile Subduction Zone which has not ruptured in a large earthquake since 1877. Therefore this array monitors for the first time the interaction of earthquake activity on the subduction zone interface and a trench-parallel fault in the overriding forearc during the terminal

stages of a seismic cycle. The displacement across the fault is continuously monitored with 2 samples/min with a resolution of 1μm. We find no continuous creep for 10 of the 11 stations, but observe step-like displacement events correlated in time with far field megathrust earthquakes or local earthquakes on the plate interface. The most prominent event recorded on all creepmeters was the Mw=8.8 Maule earthquake in 2010 located 1500km to 1800km away from the creepmeter array. All of the stations showed a triggered sudden displacement event 6–8 min after the main shock, at the same time of the arrival of the surface waves recorded at a nearby IPOC seismic station. This points to a dynamic triggering process caused by transient stress changes during passage of the surface wave. Investigation of smaller seismic events with Magnitudes <6 located close to a creepmeter with a co-located Broadband seismometer show step-like displacement events that are triggered during P and S wave passage, pointing to static stress changes directly related to the faulting process for proximal events. Our observations point to a fault system at critical state that can be triggered by very low stress perturbations.

Effects of Topography and Surface Loads on Earthquakes and Faulting

Poster Session · Wednesday · 30 April · Cook/Arteaga

Crustal Deformation from Surface Loading in the Great Salt Lake Region

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We estimate the 3-component surface displacements associated with loading due to the Great Salt Lake volume variations between 1998 and 2013 using GPS stations located around the lake in North Utah. The vertical and horizontal displacements observed are inversely correlated with the lake stage levels. Our goal is to use the observed response of the Earths crust to estimate its elastic properties. To do this, we model the interaction of the Earths surface with the load. We use topographic, lake stage, groundwater, and atmospheric pressure data with an elastic half-space model of the earth to estimate the surface loading and response in the study region. We invert the observed deformation to estimate the Youngs modulus from which other seismic properties of the crust can be inferred.

Heterogeneous Initial Stress States for Dynamic Rupture Propagation in the 2008 Mw 7.9 Wenchuan Earthquake

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We perform three-dimensional dynamic rupture simulations to investigate initial stress states along a branched fault system that can reproduce major features of rupture propagation in the 2008 Mw 7.9 Wenchuan earthquake. These features include (1) dynamic branching between the steeply dipping Beichuan fault and shallowly dipping Pengguan fault, (2) incomplete slip partitioning between the two faults, i.e., oblique, rather than strike-slip, faulting on the Beichuan fault, though primarily thrust-slip faulting on the Pengguan fault, (3) triggered rupture on the Beichuan fault about 40 km to NE of the hypocenter and backward rupture propagation from there to SW on the Beichuan fault. We use a finite element method to simulate dynamic rupture propagation on the faults and seismic wave propagation in a 3D medium on supercomputers. We find that heterogeneous initial stress states are needed to reproduce the above features in rupture propagation of the 2008 event. Important features in heterogeneous initial stress states from dynamic rupture models include (1) significantly higher differential stresses at shallow depth on the SW segment of the Beichuan fault, (2) smaller angles between the maximum principal stress and the fault strike on the fault system at about 40 km NE of the hypocenter where triggered rupture occurred, and (3) narrow ranges of initial stress states that permit simultaneous rupture along the two faults. These features in initial stresses correlate well with the existence of the Pengguan massif along the SW segment of the rupture and the Xiaoyudong fault about 40 km to NE of the hypocenter. In particular, with significant topography along the SW segment and opposite effects of topographic stress with respect to tectonic stress there reported by recent studies, the first feature suggests that the SW segment of the Beichuan fault either experienced a longer tectonic loading period or a faster thrust stress accumulation rate before the 2008 event.

The Influence of Stresses from Topography on the 2008 Wenchuan, China Rupture: Implications for Tectonic Stresses and Rupture Processes

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The 2008 Wenchuan, China earthquake is notable for the heterogeneity of slip magnitude and rake along the fault patch. The earthquake also occurred at the base of the Longmen Shan, one of the steepest and highest mountain ranges on earth. In this work, we investigate whether stresses in the upper crust from the weight of the Longmen Shan affect faulting in the region. Particularly, we explore whether stresses on the fault from topographic loading may have impeded or promoted fault slip, and to what degree the fault slip heterogeneity may be explained by heterogeneous topographic stresses. We calculate topographic stresses using standard elastic halfspace techniques. We convolve a digital elevation model of topography with Green's functions derived from Boussinesq's solutions for a vertical point load at the surface of a halfspace, then correct for the irregular surface boundary and spreading forces from topography above the halfspace. Stresses are then projected onto the fault plane. We find that topographic shear stresses on the fault are on the order of 10 MPa, and in general opposed to the direction of fault slip. Topographic normal stresses are up to $\sim$80 MPa and are highly variable. Because shear stress from topography and fault slip are opposed, we infer that tectonic stresses overcame topographic stresses during the Wenchuan event; this allows us to use topographic stresses to place minimum bounds on the magnitude of tectonic stress at the time of rupture, with trade-offs between these quantities and lithostatic pressure, pore fluid pressure, and fault friction. Additionally, a negative correlation between slip magnitude and topographic normal stress magnitude suggests that normal stresses may influence fault arrest.

Coseismic Slip in the 2013 Lushan, China Earthquake and Topographic Fault Loading

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The 2013 Mw6.8 Lushan, China earthquake primarily ruptured a steeply dipping blind thrust fault along the Longmen Shan fault zone (LMSF), to the southwest of the 2008 Mw7.9 Wenchuan earthquake. The LMSF region is characterized by extremely high topographic relief and gradient. Both the Lushan and Wenchuan earthquakes occurred on primarily NW dipping faults, range-parallel reverse faults. Strong motion data from the Lushan event reveals a relatively compact, almost entirely thrust-sense slip patch during the Lushan earthquake, in contrast to the highly heterogeneous rake and slip magnitude inferred in the larger Wenchuan event. Additionally, there is some suggestion in the strong motion data from the Lushan event of normal-sense slip on a parallel SE-dipping fault in the reverse fault's hanging wall. Regardless of whether this antithetic fault ruptured in the Lushan earthquake, it is clearly delineated by aftershocks, and is likely an important structure in the Lushan earthquake story. Both the main thrust slip in the Lushan earthquake, as well as the possible normal slip on the adjacent structure, was in the opposite sense to the direction of fault shear stresses due to topographic loading. This suggests that the main thrust slip (and potential antithetic normal slip) in the Lushan earthquake was responsible for building topography. Due to the close proximity of the two structures active in the Lushan earthquake, it is likely that they are influenced by the roughly the same background tectonic stress. Utilizing the topographic stresses, and assuming that coseismic slip is in the direction of the maximum shear stresses resolved on the faults at the time of the rupture, we constrain the tectonic stresses using several scenarios consistent with coseismic slip in the Lushan earthquake inferred with strong motion data.

Coulomb Stress, Surface Displacement and Seismic Rate Changes Associated with Ice Mass Fluctuations on Seasonal, Annual, and Decadal Time Scales in South Central Alaska

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Between Yakutat and Cordova in southern Alaska, large ice mass fluctuations occur in a region of upper crustal faulting and folding associated with collision and accretion of the Yakutat terrane. Following the Little Ice Age, glacial retreat in this area commenced in the late 19th century. The last great earthquakes occurred in 1899. For the Chugach-St. Elias region, GRACE 1 degree x 1 degree mascon estimates indicate a general trend of annual ice mass loss (2003–2012) but with large, variable seasonal mass fluctuations. For comparison to PBO GPS site positions, surface displacements and incremental stress changes associated with annual and seasonal ice and snow changes were calculated using PyLith 3-D Finite Element Model (FEM). To empirically evaluate the influence of short-term ice fluctuations on fault stability, we compared the seismic rate ($M>1.8$) from a reference background time period against other time periods with variable ice or tectonic change characteristics. After probable icequakes were removed from

the AEIC catalog, we found that the frequency of small earthquakes increased significantly in the 2002–2006 warmer time interval relative to the reference time period of 1988–1992. Additionally, there was a significant increase in these small events in the late summer and fall especially in warmer years such as 2004/5. To calculate the longer-term influence of Little Ice Age retreat on Coulomb stress changes on regional faults, we are using PyLith assuming a linear Maxwell viscoelastic Earth model. Our earlier 2-D TECTON FEM calculations suggest cumulative changes over 80 years of 0.2–1.2 MPa along the main thrust zone between the Gulf of Alaska coast and epicenter of the 1979 St. Elias earthquake.

The Role of Frictional Softening and Erosion on Thrusting Sequences in Accretionary Prisms Based on Sequential Limit Analysis

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Sequential Limit Analysis method is applied here on sedimentary rocks accreted by tectonic compression above a basal écollement (such as accretionary prisms) in a 2D vertical cross-section with uniform properties. Each shortening increment combines a thrust fold (TF) kinematics inspired by fault-bend folding, and a mechanical optimization to select the TF parameters (position along the décollement and dips of the ramp and of its conjugate shear plane) that require the minimum tectonic force. The rocks are described by their density, the Coulomb criterion, and a drop in the friction angle on the active ramp (friction softening). At each increment, a new TF is initiated if it provides a lower force than the currently active one. The life-span of a TF results from the competition between frictional softening and the uplifted mass in the current TF hanging wall.

Without softening, a new TF is activated at each increment, and this results in a ductile-looking deformation. History of the position of the active TF within the prism can be followed for millions of years, and it reveals a chaotic behaviour in the form of an extrem sensitivity to surface perturbations. However, a statistical analysis reveals a step-wise distribution of slip on the décollement, that can be explained by a simple geometric construction.

Frictional softening (i) perturbs the slip pattern on the décollement, (ii) provides a finite life span to every TF and a finite thickness to thrust sheets and, (iii) creates a long-term cyclicity of activation of the accreting frontal region and recurrent activation of the large ramps in the back of the prism. This long-term recurrence is modulated by the accreting sedimentary flux.

A simple, sand-box like, erosion law prolongs the activity of a given thrust-fold and provokes the formation of imbricate fans, duplexes, and the exhumation of deep materials, very much as observed in real settings (e.g., Taiwan, New Zealand, and analogue models).

Emergence of Continuously Recording Very Large Array Capabilities in Seismology

Poster Session · Wednesday · 30 April · Cook/Arteaga

Retrieval of Core Phases from Ambient Noise Cross-correlation Using a Dense Large-aperture Broadband Array in Southwest China

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With the deployment of very large broadband seismic arrays, there has been an explosion in the use of continuous seismic records as well as new techniques applied to dense arrays.

From early 2011 through the end of 2013, more than 350 broadband portable seismic stations were deployed in southwest China. These stations, combined with the existing 88 broadband permanent stations, composed a dense large-aperture array covering a ten by ten degree area with average station spacing of less than 50 km.

We calculated daily cross correlation functions (NCFs) up to 3600s using the vertical component of those 435 broadband stations using two years of continuous records. After stacking all daily NCFs of each path into one reference NCF, a further spatial stack, referred to as array interferometry, was conducted by stacking NCFs with similar inter-station distances into one trace.

After applying array interferometry, we observe strong signals that arrive after the fundamental surface wave. By analyzing the travel times of these signals, we clearly identify the core reflected ScS around 900s and the twice refracted PKIKP2 phase around 2400s. Moreover, these also exist strong signals from 3000s to 3600s, which could be PcPPKPPKP and PcPPKPPKS. The temporal variability of the amplitude of ScS and PKIKP2 show positive correlation with the global seismicity, implying those core phases may originate from the long lasting scattered coda waves of significant earthquakes.

Our results, combined with previous results using USArray (Lin et al., 2013), show that core phases can be extracted wherever high-density arrays exist. The geometry of sampling of the earth's deep interior can therefore be improved using array interferometry, overcoming the limitation of earthquake-station geometries. Further work on better understanding the detailed waveforms of the spatial stacked NCFs are still necessary in order to use those signals to investigate deep earth structure.

An Earthquake Detection Algorithm with Pseudo-Probabilities of Multiple Indicators

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We develop an automatic earthquake detection algorithm combining information from numerous indicator variables in a non-parametric framework. The method is shown to perform well with multiple ratios of moving short- and long-time averages having ranges of time intervals and frequency bands. The results from each indicator are transformed to a pseudo-probability time-series (PPTS) in the range [0, 1]. The various PPTS of the different indicators are multiplied to form a single joint PPTS that is used for detections. Since all information is combined, redundancy among the different indicators produces robust peaks in the output. This allows the trigger threshold applied to the joint PPTS to be significantly lower than for any one detector, leading to substantially more detected earthquakes. Application of the algorithm to a small data set recorded during a 7-d window by 13 stations near the San Jacinto fault zone detects 3.13 times as many earthquakes as listed in the Southern California Seismic Network catalogue. The method provides a convenient statistical platform for including other indicators, and may utilize different sets of indicators to detect other information such as specific seismic phases or tremor.

Recovering Seismic Green's Functions Using Icequake Coda Interferometry at Erebus Volcano, Antarctica

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Seismic interferometry has emerged in the past decade as a powerful technique for interpreting passive seismic data and has been particularly useful for retrieving portions of elastic Green's functions in continental settings and for detailing structure and monitoring temporal variations at microseism periods (e.g., near 8 Hz) at volcanoes. Coda wave interferometry studies to retrieve body waves have previously been performed on Erebus volcano utilizing Strombolian eruption coda signals to image the internal structure of the volcano using short period body waves. Here we demonstrate that short-period surface and body wave Green's functions can also be recovered by correlating icequake coda signals on this highly glaciated volcano. A dense network of 99 short-period, three-component seismometers were deployed in a 3 × 3-km array surrounding the summit crater during the 2008–2009 austral summer. Coda data from near-surface source icequakes (likely crevassing events) recorded during the month of December 2008 were cross-correlated revealing both body- and surface-wave portions of the Green's functions across the array. Recovery of Green's functions utilizing icequake coda can be used to enhance recovery of structural details and has possible monitoring applications on glaciated volcanoes.

Determining the Geometry and Kinematics of an Earthquake Fault using Seismic Gradiometry

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Seismic wave gradiometry relates the spatial gradients of the wavefield to the velocity and radiation pattern through two spatial coefficients in up to three dimensions. The first coefficient relates to the vector slowness of the wavefield and has been the subject of most current gradiometry research. The second coefficient gives the amplitude change as a function of position and direction along the wavefront (i.e. the radiation pattern) and is directly related to the seismic moment tensor. In principle, it should be possible to invert for the parameters of the seismic moment tensor using the spatial derivatives of the wavefield and an assumed seismic source model. In this

work, we explore the feasibility of inverting the P-wavefield for the parameters of the seismic moment tensor. We assume that the data are recorded in the far field and that the earthquake source is pure double couple dislocation described by the strike, dip, and rake of a fault.

We start with a partial differential equation relating the P-wave radiation pattern to the spatial derivatives of the seismic wavefield. We attempted a finite difference solution to this equation, but found that we obtained only a trivial solution. However, we find that a computationally intensive grid search algorithm can return the fault parameters of a double couple model.

Rupture Speeds of Recent Large Earthquakes

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Studying the rupture speeds of earthquakes is of broad interesting for earthquake research because it has a large effect on the strong near-field shaking that causes damage during earthquakes. Also rupture speed is a key observation for understanding the controlling stresses and friction during an earthquake, yet the speed and its variations are usually difficult to determine. Using only far-field seismic waveforms, which is the only data available for many large earthquakes, there are problems for estimating the rupture speed with standard waveform inversions, due to trade-off between the rupture speed and the slip location.

Here we applied a back projection method to estimate the rupture speeds of Mw = 7.5 strike-slip earthquakes since 2001 which could be analyzed using Hi-net in Japan. We found that all events had very fast average rupture speeds of 3.0–6.0 km/s, which are near or greater than the local shear wave velocity (supershear). These values are faster than for thrust and normal faulting earthquakes that generally rupture with speeds of 1.0–3.0 km/s. Considering the depth-dependent shear-wave velocity, the average propagation speeds for all of the strike-slip events are closer to or greater than the shear wave velocity. For large strike-slip events, transition from subshear to supershear usually occurs within distances of 15 to 30 km from the initiation, which is probably the reason for the scarcity of observed supershear earthquakes for smaller magnitudes.

Earthquakes with supershear ruptures can cause more damage than events with subshear ruptures because of the concentration of energy in the forward direction of the rupture. Numerical modeling shows strong focusing and other effects of energy at the rupture front which can intensify the ground motions. Careful evaluation of long and straight strike-slip faults should be emphasized for predicting strong ground motions due to supershear rupture.

Earthquake Locations using a Wave Gradiometer in Southern Illinois

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The Center for Earthquake Research and Information (CERI) deployed a surface gradiometer array to observe aftershocks from the 2008 M5.4 Mt. Carmel, Illinois earthquake. The array consisted of 5 instruments arranged in a square finite difference star with 25 meter spacing and a center element designed for waves with 0.2km to 2km wavelengths. The array recorded local aftershocks and quarry blasts. Quarry blast data enable tests of gradiometry-derived wave attributes with this array and yield azimuths within 10 degrees of the inferred quarry locations. We then use azimuth and slowness estimates determined from gradiometry to help locate aftershocks. Results are compared to published event locations. Horizontal determination of epicenters can change by up to 10 km and as little as 10 meters from published results. Slowness determinations had relatively poor resolution and placed the earthquakes within the same 20 km thick layer in the velocity model. We also compare results between wave polarization analysis and gradiometry to infer azimuths to events. One method of polarization analysis to find azimuth consisted of minimizing the energy within a P wave time window in the transverse component. We found that propagation azimuth determinations could be very similar between techniques but were dependent on choice of time windows and data filter parameters.

Explosive Source Characterization

Poster Session · Wednesday · 30 April · Cook/Arteaga

Understanding Shear Motion from Underground Explosions in Granite

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This work is focused on analysis of near-field measurements recorded during Source Physics Experiments as well as experiments conducted in central New Hampshire. One of the main goals of these experiments is to investigate the possible mechanisms of shear wave generation in the nonlinear source region. Experiments revealed significant tangential motion at many locations. Furthermore, azimuthal variations in radial velocities were also observed which cannot be generated by a spherical source in isotropic materials. Understanding the nature of this shear motion is important for discriminating between the natural seismicity and underground explosions signatures. Possible mechanisms leading to such motion include, but are not limited to, heterogeneities in the rock such as joints, faults and geologic layers as well as surface topography and vertical motion at the surface caused by material spall and gravity. We have performed 3D computational studies considering all these effects. We assume that the rock has preexisting fractures which can modify radial motion from the source based on local conditions such as friction, water saturation and fracture orientation. Also, in repeatable events these conditions may change due to the damage closer to the source and at the boundaries between various layers. We use history variables in the model which describe damage accumulation both at the preexisting fractures and in the continuum to model new fracture generation. Results of our studies in the near field can be used to build a better source model for seismic wave propagation from underground explosions which includes information from the site characterization.

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Coupled Non-linear and Linear Acoustic Wave Propagation Codes for Explosion Monitoring

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Seismic and acoustic signals emanating from explosions are powerful phenomenologies that can be exploited for detection, identification and characterization. However, accurate and reliable identification of events requires the ability to model both the source physics and propagation of seismic and acoustic waves to global and regional monitoring stations. The ability to accurately simulate explosions is critical for nuclear monitoring, forensic evaluations and scenario modeling. Nonlinear algorithms such as Sandia's CTH code can simulate the actual explosions, but they are inefficient and inaccurate at propagating these signals at great distances. A linearized wave propagation code, coupled to a nonlinear code, provides an efficient mechanism to both accurately simulate the explosion itself and also propagate these signals to distant receivers. We have successfully coupled radCTH and SNL's linearized acoustic code, Acousti, for a simple test case. We will present results of this coupling simulation. The shape of the domain of coupling between linear and non-linear algorithms and the distance at which the coupling is implemented can affect far field wave amplitudes and shapes. This provides a means of investigating how the wavefield evolves toward linearity as a function of distance from an explosive source. The approximate distances where the wavefield is sufficiently close to linear will also be explored. Ultimately, the code can be validated with observations obtained from the Source Physics Experiment.

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Comparing Modeled and Observed Infrasound Signals from the Source Physics Experiment Tests 2 and 3

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The overall mission of the Source Physics Experiment is to improve upon and develop new physics based models for underground nuclear explosions using scaled, underground chemical explosions as proxies. Jones et. al, (AGU 2013) previously presented results describing the use of the Rayleigh integral (RI) to model the source region of the SPE explosions. These results showed that the source region could be easily and accurately modeled using the RI. We follow-on to this work by analyzing and modeling infrasound data collected during SPE-3. This test was designed to be as similar as possible to SPE-2 and although the tests were similar in yield, we

observed a reduction in peak acceleration and pressure amplitudes. We hypothesize that this could be due to the 'damage zone' from the previous test.

This work was done under award number DE-AC52-06NA25946. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

USArray Acoustic Capabilities Confirm Significant Meteor Sighting

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The addition of atmospheric acoustic sensors as part of the transportable stations of USArray have allowed a detailed explanation to be provided to the public and media regarding a recent significant meteor event observed over the region of Montreal, Canada on night of November 26, 2013. The meteor, obscured by cloudy conditions after a winter storm, was perceived by residents only as a bright blue flash followed subsequently by loud thunderous sounds and rumbling. Being unusual and occurring during early evening hours, the event quickly became a source of great public interest, prompting significant media attention. The acoustic event went nearly unobserved by all regional seismic instruments, but was a significant source of infrasonic sound readily recorded by USArray barometric and microbarometric sensors currently operating in the region.

Infrasonic recordings of ballistic shockwaves, characteristic of a hypersonically travelling object, were observed between Montreal, QC and Malone, NY, while the object's apparent subsequent break-up was recorded over hundreds of kilometres to the ESE and constrain the object to a generally north-south trajectory. With no reported predictions of the re-entry of orbital debris, the source of the event was most-likely that of a sizable meteoroid. Size estimates for the meteoroid, based on signal characteristics and theoretical and empirical relationships, range between 0.2 - 0.6 m in diameter for a spherical body, depending upon its velocity which remains constrained but unknown. Any meteorites that may have resulted from the event have not been identified to-date, yet due to the presence of USArray acoustic capabilities a detailed explanation to this highly unusual event was able to be provided to media for public consumption from trusted sources, where speculation and conjecture may have otherwise run rampant.

Fiber Optic Acoustic Sensing (FOAS) Far-Field Observations of SPE 3

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Fiber Optic Acoustic Sensing (FOAS) is a relatively new sensor that uses the fiber optic cable itself to measure strain induced by seismic and acoustic waves (e.g. both vector and scalar waves). Here we show results from two deployments recorded during a Source Physics Experiment (SPE) shot (SPE3). One dataset is from a long (~30 km) roughly linear deployment approximately radial to the source and the second is a shorter (~3 km) deployment at a higher angle to the source. Equivalent sensor spacing is on the order of 10 and 16 m, respectively, although the signal represents an average rather than a point measurement. We compare the FOAS time series data with nearby seismic sensors. Relative amplitudes appear slightly anomalous compared to the seismic sensors and the FOAS signal-to-noise ratio is generally lower. We generate simple synthetics by calculating linear strain using a 3D finite difference code and compare with observed results. The FOAS data appears useful for arrival times. Currently, we lack a well-defined instrument response and therefore techniques that require absolute calibration are difficult although relative calibration may be possible. We note that FOAS technology is rapidly improving and these issues may be addressed in the future. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Waveform Analysis of Scholte Waves Observed in San Diego Trough using a Seafloor Source and OBS

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A seafloor sound source has the fundamental advantage over a surface ource of releasing its energy much closer to its sub-sea sediments. It an produce abundant shear-wave energy. Since marine mammals spend most f their time near the surface, a seafloor source reduces their exposure to damaging acoustical signals. Dorman and Sauter, 2006, Geophysics, designed and built an implosive source for deep/seafloor use. Our existing device is designed to operate down to a depth of 2000 meters. It uses a two-stage valve that allows rapid flooding of a 20-liter cylinder. This volume is has the same moment as 1/4 kg of explosive fired at 800 meters depth, although the source signature islonger.

This source is effective in exciting interface (Scholte) waves whose dispersion is diagnostic of the shear wave structure of the seafloor sediments. We earlier analyzed data from the San Diego Trough (SDT) by matching observed and calculated group velocity dispersion, and now extend that analysis to waveform analysis as done earlier for explosive-generated waves by Nolet and Dorman, 1996, GJI. We modeled the explosive source using the hydrocode SIN.

The goal of the waveform analysis is to produce a good-enough model to use as a Greens function to extract the time history of the source moment. We currently do not have a good dynamic model of the implosive source, but do know its moment.

Seismic-Wave Gradiometry Applied to a Small-Scale Exploration Dataset

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Seismic-wave gradiometry is an array-processing technique that utilizes spatial gradients between receivers to give information about wave timing and amplitude that can be applied to many geophysical problems. The concepts of 2D seismic-wave gradiometry are explored using a huddle test and three small-scale experiments with 24 vertical geophones and sledge hammer sources. A huddle test is performed to calibrate the geophones. Results show that relative gains cannot be completely characterized because of geophone/ground interaction. Synthetic tests show that 3% gain errors introduces errors of up to 3% into gradiometry-derived wave attributes. A standard linear refraction array is constructed to investigate the slowness and frequency content of hammer sources in order to understand induced and ambient wavefields recorded by two gradiometer designs. One design consists of four, six-instrument gradiometers in a linear array to investigate the spatial/temporal variation of horizontal slowness, wave azimuth, radiation pattern, and geometrical spreading for sources close to the array as well as test the location abilities of the gradiometer array. The gradiometers were able to correctly determine the slownesses of the P-waves and surface waves identified in the refraction profile. A second gradiometer experiment involves four superimposed cells to explore precision in calculation of spatial gradients. This analysis was done for combinations of the eight center stations for refracted P-wave and surface wave arrivals. Refracted P-wave slowness precision increased by 70% and azimuth precision increased by 66% when two center stations were used instead of one. For a surface wave arrival, the slowness precision increased 57% and the azimuth precision increased 99% when two center stations were used instead of one. These small-scale experiments show that off-the-shelf geophones may be used to build useful gradiometer arrays.

Yield and Depth of the SPE Chemical Explosions by Modeling of Local Waveforms Using a Source Consisting of Pure Explosion and Spall Sources

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Regional waveforms generated by nuclear explosions are often used to invert for the moment tensor matrix to estimate the seismic moments of the isotropic, compensated linear vector dipole (CLVD) and double couple (DC) sources. In this paper, we modify this conventional approach to a grid-search technique assuming that the sources of the SPE chemical explosions consist of two mechanisms, isotropic and spall. In a separate analysis, we also include an additional DC source known to exist at a close proximity to the shot point. There is strong evidence of spall on the surficial accelerograms recorded very close to the shot point as well as that of a steeply dipping fault in the area surrounding the shots. The relative timing of the spall signal and dwell provide basic information regarding their delay time as well as their strengths relative to first P arrivals. We use this information in generating spall seismograms, assuming that source is equivalent to a vertically symmetric CLVD source or a vertical single force. In the single force formulation, we allow the force to act on the dislocation interface where the spall collapses at various depths. Synthetic spall seismograms are used in conjunction with the explosion seismograms to model recorded waveforms, determine the yield of the explosion, and seismic moment of the spall (or the CLVD) source. The source function of the explosion source is based on a time domain expression for a given yield and depth of burial (Saikia et al., 2013). For the spall and DC mechanisms, source functions are assumed to be delta functions. A sensitivity study is being conducted to evaluate the dependence of model

parameters on the depth of the spall sources. Green's functions used in this study are based on the inferred bore-hole data, but further refined to having the capability for entrapping high-frequency P and Rg waves observed from various shot points.

Resolving Focal Depth with a Near Field Single Station in Sparse Seismic Network

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Focal depth is essential for seismic hazard assessment and seismogenic studies. However, it is challenging to resolve accurate focal depth in sparse seismic network with just P and S arrival times. Here we explore a seismic depth phase for determining focal depth with a single seismic station in near field. The seismic phase is generated by S wave from the seismic event which is reflected as P wave post-critically at the free surface. For half space earth models, the phase is called free surface P wave. But for subsurface models with velocity gradient, the phase is actually summation of post-critical P wave and turning P waves. Thus it would be more accurate to be called as surface coupled P waves, and we name it as sPL. sPL is well developed for epicentral distances larger than two times of focal depth, and is usually observed for distances less than 50km. sPL arrives before S wave and only shows up on radial and vertical components without presence on tangential component. Moreover, sPL is stronger on radial component than on vertical component. With examples for the 2013 Lushan (China) M7 earthquake sequence and the 2011 Virgina earthquake sequence, we demonstrate that focal depth of aftershocks can be well resolved from differential time between P and sPL with a single stations.

Isotropic Source Rerms of San Jacinto Fault Zone Earthquakes based on Waveform Inversions with a Generalized CAP Method

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We analyze source tensor properties of seven Mw > 4.2 earthquakes in the complex trifurcation area of the San Jacinto Fault Zone, CA, with a focus on isotropic radiation that may be produced by rock damage in the source volumes. The earthquake mechanisms are derived with generalized 'Cut and Paste' (gCAP) inversions of 3-component waveforms typically recorded by >100 stations at regional distances. The gCAP method includes parameters zeta and chi representing, respectively, the relative strength of the isotropic and CLVD source terms. The results indicate statistically significant explosive isotropic components for at least six of the events, corresponding to $\sim$0.2–5% of the total potency/moment of the sources. The possible error in the isotropic components due to station variability is quantified with bootstrap resampling for each event. Tradeoff and correlation between the isotropic and CLVD components are studied using synthetic tests with realistic station configurations. The associated uncertainties are found to be generally smaller than the observed isotropic components. Two different tests with velocity model perturbation are conducted to quantify the uncertainty due to inaccuracies in the Green's functions. Applications of the Mann-Whitney U test indicate statistically significant explosive isotropic terms for most events consistent with brittle damage production at the source.

Full Moment Tensors for Small (Mw < 3) Events at Uturuncu Volcano, Bolivia

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We use seismograms from a deployment of 24 broadband stations on Uturuncu volcano, Bolivia, to estimate full moment tensors for small (Mw $<= 3$) crustal earthquakes. We adapt the grid-search moment tensor inversion method of Zhu and Helmberger (1996), which considers first motion polarities, body waves, and surface waves; and use a parameterization of seismic moment tensor in terms of its eigenvalues (magnitude, isotropic, CLVD) and orientation (strike, dip, rake). Performing a full grid search on these parameters allows us to estimate uncertainties. The majority of events are in the range $0 <= \text{Mw} <= 1$ and allow use of only P-wave polarities which results in larger parameter uncertainties, but our representation of misfit over parameter space still enables us to discriminate among different earthquake mechanisms. For the largest events (Mw > 2) we are able to include full seismograms in the inversion, which reduces uncertainty estimates for the moment tensors. We also explore whether different subsets of waveforms (e.g., surface waves only or polarities only) will produce consistent moment tensors. The ability to resolve all six parameters, notably isotropic and CLVD, depends strongly on station coverage and signal-to-noise level in the seismogram. We present a comprehensive full moment tensor catalog for crustal events at Uturuncu volcano, with uncertainties in source mechanisms depicted visually on the fundamental lune of eigenvalue space.

We use the lune to interpret the catalog, whereby crack tensors are at the boundary of the lune and double couple tensors are at the center. We find a predominance of source mechanisms with positive isotropic components, which we interpret as an indication of tensional crack processes beneath the volcano.

Time-Dependent Moment Tensors of the First Three Source Physics Experiments Explosions

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Using mainly vertical, high frequency geophone data recorded within 2 km from the Source Physics Experiments (SPE) explosions, we conduct frequency-domain moment-tensor inversions to retrieve time-dependent moment tensors of the first three SPE explosions. Building on a velocity model developed using P-wave travel times and Rg phase velocities for one of the radial arrays (Line 2), we constructed an attenuation model by fitting synthetic P-wave and Rg amplitude decay to those of observed seismograms. The one-dimensional velocity model along with attenuation is used in the moment-tensor inversion to calculate Green's functions. We select data from all radial arrays that have P-wave travel time, Rg phase velocity and amplitude decay consistent with those of the Line-2 data. The inverted moment tensors are dominated by diagonal components. The source spectra show long-period levels consistent with predictions from a Mueller-Murphy nuclear-explosion source model for granite, the rock type at the SPE site, with modified Denny-Johnson cavity-radius scaling. Among off-diagonal moment-tensor components, Mxy (horizontal double-couple) have the largest peak amplitude. We also attempt to resolve the damage source that accompanies the explosions with a modified inversion scheme. Using the new scheme, we invert for two sources: an explosion and a damage source at a shallower depth. By systematically changing the depth of the damage source and comparing the predicted seismograms with input seismograms in a grid-search approach, we map the depth extent of the material damage during the explosions. It appears that most of the damage occurs within the weathered layer near the free surface for SPE explosions.

A Spall Model Comparison with Insights from the Source Physics Experiment

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Spall signals from the Source Physics Experiment (SPE) are presented, analyzed, and modeled for insight to the explosion source. The observed signal is similar in nature to nearby historical nuclear explosions and the surface force-time history or velocity can be interpreted with the same model. We forward model the surface accelerometer records to estimate peak spall velocity, spalled mass, and spall depth and radius. These values are consistent with the disturbed area in the shot region. The spall signal is also investigated with a 3D continuum model that incorporates gravity and where there is good agreement between predicted and observed velocity. 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-648205.

Local Distance Application of P/S Methods of Discriminating Explosions from Earthquakes – How Low Can We Go?

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Over the past twenty years regional distance (200–1600 km) high-frequency seismic P/S wave amplitude ratios have proven very empirically effective at identifying explosions among a background of natural earthquakes. However the physical basis for the generation of explosion S-waves, and therefore the predictability of this P/S technique as a function of frequency and event properties such as size, depth, geology and path, remains incompletely understood. A goal of current research, such as the Source Physics Experiments (SPE), is to improve our physical understanding of the mechanisms of explosion S-wave generation and advance our ability to numerically model and predict them. At regional distances the lithospheric waveguide usually allows P/S discriminants to be applied over broad areas using relatively simple 1- or 2-D path corrections. The main caveats to P/S discriminant effectiveness are: 1) the signals need to be sufficiently high frequency (usually $>\sim$2 Hz, sometimes higher) and the path attenuation must allow source generated S-waves to still be visible at the frequencies and recording stations of interest.

As we push the identification of explosions to even smaller yields and magnitudes less than 3, we need to examine P/S behavior at closer, local distances

and even higher frequencies. We are using the new SPE data along with small historic nuclear tests to investigate local P/S discrimination. Interesting new results include: 1) The explosion P and S corner frequencies appear to be similar, in contrast to some model predictions; 2) The SPE 1-ton chemical explosions appear to discriminate well from background earthquakes in the frequency band 4–8 Hz at 200 km, similar to larger nuclear tests, and 3) P/S discrimination for SPE shots at local distances is poor at some stations across a broad range of frequencies from 4–64 Hz. We are investigating strong structural focusing as a potential complicating issue with local distance P/S discrimination.

Source Physics Experiment Site Characterization: Earthquake Relocation and Southern Nevada Attenuation Structure

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The Source Physics Experiments (SPE) are a series of ongoing experiments designed to improve our physical understanding and modeling capability of explosive seismic sources. A candidate SPE would provide a direct comparison of earthquake and explosion sources by drilling to the well-constrained hypocenter of a shallow earthquake and detonating a chemical explosion; recording both types of events with the same seismic network. A sequence of unusually shallow events occurred in southern Nevada in May of 1993, including 12 events with magnitudes over 2.0, providing an ideal opportunity for this experiment. The events were well recorded at temporary stations deployed by UNR. Eight new seismic stations, including two borehole sensors, located at the original 1993 sites and additional sites, have been installed and ongoing seismicity along the fault is currently being recorded.

In order to ensure the best possible siting for the explosion, we relocate both the historic earthquake sequence and recent seismicity using the multiple-event location algorithm Bayesloc, which formulates the problem as a hierarchy of the travel time model, arrival time model, and a prior model for each parameter. For comparison, we also determine HYPODD locations. We use a local network with a similar azimuthal distribution and precisely known locations of nearby previous nuclear tests as a proxy to estimate the accuracy of our earthquake locations. In addition, we perform a seismic amplitude tomography to ensure that the explosion is large enough to be recorded at all stations of interest over a reasonable frequency range, and to assist in waveform modeling. The tomography uses surrounding earthquake seismicity and seismic networks to determine high-resolution local and regional P and S-wave attenuation structure in the crust and upper mantle.

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High Resolution Imagery of the Source Physics Experiment Site using Seismic Interferometry

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The purpose of the Source Physics Experiment (SPE) is to obtain a physics-based understanding of how seismic waves are created at and scattered near the source. In order to separate source-specific effects from those due to geological heterogeneity, we need a precise picture of the subsurface. In this study, we use several methods of seismic interferometry to obtain highly detailed images of the SPE site. Coda wave interferometry (CI) uses the diffuse coda from earthquakes or explosions as a source of coherent energy. Ambient noise correlation (ANC) uses the energy of the ambient background field. In each case, the data recorded at one seismometer are correlated with the data recorded at another to obtain an estimate of the Green's function (GF) between the two. We used the records of the SPE shots as an energy sources for the CI technique and several months of high gain continuous data for ANC.

Each technique has advantages over the other. CI is very fast, and the GF obtained has the same frequency content as the original shot. Using CI on the SPE data, we obtain very good quality estimate of the GF to very high frequency. The key disadvantages of CI are that we can only correlate energy propagating radially outward and the source point itself is hidden. ANC requires more data and processing time, but allows us to estimate the GF between any two of the seismometers. By combining the two techniques, we obtain a very sharp image of seismic velocity and attenuation in the upper several kilometers beneath the site. Using CI, we recovered 860 high quality GFs along the 5 main lines. ANC gave us several thousand more, including paths that cross the source point and between the lines. We calculate synthetic seismograms through the 3D model to validate the results and to predict the source propagation for different shot geometries.Our end result is a fully 3D tomogram of the subsurface with lateral resolution as small as 100 m.

3D Modeling of Rg Wave Propagation on Geophone Lines Recording the Source Physics Experiment

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The Source Physics Experiments (SPE) involve chemical explosions detonated in a heterogeneous geologic setting. High-frequency Rayleigh waves, called Rg, are sensitive to variations in Earth structure. Observed Rg waves recorded along five lines of geophones extending radially from ground zero with offsets from 100 to 2000 m and station spacing of 100 m exhibit strong azimuthal variations of attenuation properties. Lines #3 and #4 show evidence of scattering and reverberations, which suggest the presence of major structural changes and/or boundaries along these lines. We present results of a 3D modeling study with the Spectral Element Method (SEM) to evaluate which structural features have the greatest influence on the observed variations. In a preliminary study (Larmat et al., 2013), we demonstrated that surface topography around the SPE site has minor effect on Rg waves for the distance and frequency ranges considered in that study (below 2km; 2 to 8Hz). In contrast, previous 2D modeling results have shown that a near-surface, thin, weathered layer of varying thickness and low wave speeds plays a major role on the observed waveforms. The elastic and attenuation models considered in this study will be constrained by our understanding of the geologic setting as well as by data analysis and 2D forward modeling (e.g. Rowe et al., this meeting). The effects of varying wave speeds of the medium and thickness of the weathered layer will be the focus of this study.

Structural Heterogeneity at the SPE Site Revealed Through Combined P-Wave Travel Times and Sub-Band Rg Phase Velocities

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We present analyses of the two-dimensional (2-D) seismic structure beneath Source Physics Experiments (SPE) geophone lines that extended radially at 100 m spacing from 100 to 2000 m from the source borehole. With seismic sources provided only at one end of each line of geophones, standard refraction profiling methods are unable to resolve the seismic velocity structures unambiguously. In previous work we have shown overall agreement between body-wave refraction modeling and Rg dispersion curves for the least complex of the five lines, Line 2, leading us to offer a simplified 1-D model for this line. A more detailed inspection of Line 2 supports a 2-D re-interpretation of the structure on this line. We observe variation along the length of the line, as evidenced by abrupt and consistent changes in the behavior of surface waves at higher frequencies. We interpret this as a manifestation of significant material or structural heterogeneity in the shallowest strata. This interpretation is also consistent with P-wave and Rg attenuation observations. Results for Line 2 and other geophone lines will be presented.

A new Database of Digitized Regional Seismic Waveforms from Underground Nuclear Explosions in Eurasia

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Seismology is an observational science. Hence, the effort to understand details of seismic signals from underground nuclear explosions (UNEs) requires analysis of waveforms recorded from past nuclear explosions. Of principal interest, are regional signals from UNEs too small to be identified reliably via teleseismic recording.

But the great majority of stations operated today have never recorded UNE signals at regional distances, because most stations were installed long after the

period when most UNEs were conducted; and the few nuclear explosions since the early 1990s were mostly recorded only at teleseismic distances. We have therefore gathered thousands of nuclear explosion regional seismograms from more than a hundred analog stations operated in the former Soviet Union – most of them in a vast region stretching approximately 6000 km East-West and 2000 km North-South and including much of Central Asia – and have digitized them and created a modern digital database for them, including significant metadata.

Much of this work has been done in Kazakhstan. This work is complementary to the twenty-year collaborative effort (1991 to 2010) which made the original digital recordings of the Borovoye Geophysical Observatory, Kazakhstan, openly available in a modern format (see http://www.ldeo.columbia.edu/res/pi/Monitoring/Data/).

This presentation will characterize the content and overall quality of the new database of signals from UNEs in Eurasia, which were conducted across substantial ranges of yield and shot-point depth, and under a great variety of different geological conditions (for both source and station).

We note at present that openly available seismogram archives for Eurasian explosions are in several respects better than those for explosions conducted by the United States and by Western European nations, especially for the era from 1960 to about 1985. The opportunity to build and improve such archives will not last indefinitely.

High Frequency Network Discrimination Using MLE Source Spectra From Global Amplitude Tomography

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Discrimination between natural and man-made seismic sources has been performed for decades by examining differences between teleseismic surface wave and body wave magnitudes. For small events, we must augment, or replace teleseismic magnitude differences with high-frequency regional phase amplitude ratios, typically taken between different phase types or for different bands. Such studies are traditionally performed for one station at a time. However, if we correct for high-frequency path and site effects, we can combine source estimates from a network of stations, prior to forming discriminant ratios. Censored data can be included using maximum likelihood estimation (MLE) techniques, as is often done for teleseismic magnitudes.

To obtain models of attenuation and site effects, we apply two-dimensional (2-D) tomographic techniques to summary amplitudes. These amplitudes are formed by applying quality control and L1 stacking techniques to relative amplitudes for event clusters, station clusters, and all channels at each station. Amplitudes are inverted using a simultaneous multi-phase, multi-band approach that employs absolute spectral constraints on well-studied earthquakes. Multi-scale, global parameterization is obtained using GeoTess software (www.sandia.gov/geotess/). A global data set of stations and events covers all continents but Antarctica, except for portions of shield regions. Attenuation results show remarkable, high-resolution correlation with regional geology and heat flow. Our data set includes regional explosion amplitudes from many sources, including LLNL and Leo Brady data for North America, and Borovoye Archive and ChISS data for Asia. The application of MLE to shear phases, alone, is very helpful as the most critical censoring occurs for explosion shear waves. We find that L1 and L2 MLE procedures are equally effective. Our 2-D amplitude models dramatically improve high frequency P/S discrimination results.

Fault Structure, Heterogeneity, and Implications for Rupture Dynamics

Poster Session · Wednesday · 30 April · Cook/Arteaga

Modeling Fault Rupture Process by Lagrange Discontinuous Deformation Analysis Method

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Dynamic process of fault rupture caused by frictional sliding in a quasi-static stress field may be simulated by rock experiment. Suppose rock shear strength obeys the rate-state dependent frictional law. A numerical method, Lagrange Discontinuous Deformation Analysis (LDDA), is used to simulate the dynamic process. The preliminary results about fault friction evolvement and sliding characteristics obtained by the method are as follows: 1) The sliding velocity, frictional coefficient, state variable and stresses are inhomogeneous on the slide interface and dependent on time. Comparing with Coulomb's friction law, the model with rate-state dependent fraction low reveals more details about the rupturing process. 2) It is found that the shearing stress drops on the slide interface are not constant both in time and in space. 3) The maximum of the sliding velocity is not at the beginning of the sliding. 4) The frictional coefficient is determined by the slip velocity and state variable during the whole sliding process. The sliding velocity dominantly controls the frictional coefficient at early evolvement phase and the state variable mainly affects the frictional coefficient at last evolvement phase.

Re-visiting Linear Source Inversion with the Full Complexity of Earthquake Rupture, Including Both Slip Re-activation and Supershear Rupture

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Kinematic source inversion is an important research tool in investigating earthquake source by inverting seismic and geodetic data. For the last two decades, nonlinear source inversion has become popular in the community. The fast growing computational power allows us to apply global searching algorithms in the nonlinear inversion. We can estimate temporal source parameters, such as rupture velocity and slip duration, more explicitly in the nonlinear inversion. It is also beneficial to implement dynamically compatible source time functions. However, dynamic rupture models show that earthquakes may rupture in a very complex fashion, exhibiting multiple rupture fronts propagating at subshear and supershear rupture speeds, back-propagating rupture and slip reactivation (Gabriel et al. 2012) even on a single planar fault. Lee et al. (2011) show that the 2011 Tohoku-oki earthquake may have multiple ruptures, involving slip reactivation, by kinematic source inversion. Classical nonlinear inversion methods assume single slipping with a single pre-defined source time function, which may not work well to resolve such complex rupture processes. The identification of the complex rupture requires inversion methods that allow such complexities in model space. We perform synthetic source inversion tests with dynamically generated complex source models, including both slip reactivation and supershear rupture. We adopt a linear source inversion method constructing a model space with multiple time windows, allowing slip from the nucleation to the termination of rupture for every point on the fault. We adopt the Bayesian inversion to regularize model space effectively. We find that both reactivated secondary rupture and supershear rupture front can be detected well as long as they produce a significant level of seismic moment. It would be beneficial to apply the linear inversion method to check the complexity of rupture before we assume single slipping in the nonlinear inversion.

Fault Slip Heterogeneity of the 2008 Mw 7.9 Wenchuan, China, Earthquake and Implications for Regional Tectonic Stresses

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Geodetic and seismic observations of the 2008 Mw 7.9 Wenchuan, China, earthquake indicate a highly heterogeneous pattern of coseismic slip along the Longmenshan fault zone, from predominantly thrust slip on shallow dipping fault segments, towards strike-slip on more steeply dipping fault segments. Focal mechanisms of aftershocks are roughly consistent with the coseismic slip rake in the mainshock. Coseismic slip variability might be due to heterogeneity in pre-earthquake stresses, changing from compressional loading to shear loading along the fault strike. However, the correlation between coseismic slip rake and fault geometry, most notably fault dip, suggests that the heterogeneity may be due to geometric slip partitioning.

Using a probabilistic framework, we estimate stress using both coseismic slip models of the 2008 Wenchuan earthquake and the re-determined aftershock focal mechanisms from Cai et al. (2011). Our estimations are based on the assumption that faults slip coseismically in the direction of the maximum shear stress on the fault (Angelier, 1979). Rather than simply solving for the most likely estimate, our results are shown as a full posterior probability representing the likelihoods of principal stress orientations and relative magnitudes. We find that coseismic slip in the Wenchuan earthquake is consistent with a homogeneous pre-mainshock stress field, whereas aftershock focal mechanisms indicate fairly heterogeneous stresses. While these two results are seemingly contradictory, we note that coseismic stress changes in the Wenchuan mainshock are heterogeneous, and the stress inferred from aftershocks may just reflect these stress changes rather than the pre-mainshock stresses. That the coseismic slip models are consistent with a homogeneous pre-earthquake stress field, suggests that the heterogeneity of the coseismic slip is due to heterogeneity of frictional properties across the fault.

High-Resolution Geophysical Imaging Across the Olympia Structure, Southern Puget Lowland, WA: Defining a Fault System

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Linear magnetic anomalies suggest that the 80-km-long Olympia structure in the southern Puget Sound is a fault vertically offsetting Eocene Crescent Formation as much as 6 km. Northeast of the Olympia structure, Crescent Formation lies buried beneath 4–6 km of Tertiary and Quaternary strata of the Tacoma basin, whereas Crescent Formation is exposed at the surface immediately south of the Olympia structure. Although numerous marine seismic-reflection profiles have been acquired near the projected trace of the Olympia structure, its tectonic character remains enigmatic because shallow inlets of southern Puget Sound prevent the collection of deep-penetration marine seismic profiles across the geophysical anomalies. To supplement the existing marine data, we acquired 14.6 km of land-based seismic reflection data in a profile that extends from exposed Crescent basement in the Black Hills northward across the surface projection of the Olympia structure inferred from potential field anomalies. The reflection seismic data image the Crescent bedrock surface to approximately 1 km depth beneath the Tacoma basin and reveal the dip on this surface to be no greater than about 8 degrees. Although regional potential field data show a strong linear trend for the Olympia structure that implies a simple thrust fault, high resolution magnetic and gravity modeling along the land-based profile suggests that the structure is complex and possibly segmented. Assuming normal magnetization, contacts determined from boundary analysis of magnetic anomalies agree in both location and sense of movement with faults identified on the seismic profile. We propose that the seismic and potential-field data identify oblique-slip faults along the northernmost part of the Black Hills uplift. Our data further suggests that deformation of the Olympia structure changed from largely transpressive to dextral strike-slip in recent geologic time.

Rate-and-State Coulomb Stress Evolution: a Pseudo-Prospective Southern California Earthquake Forecast

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In previous studies, we confirmed an association between static Coulomb stress change and earthquake location in southern California, when resolving stress tensors onto uniformly oriented northwest right-lateral strike-slip planes (Deng & Sykes, 1997). Using an optimized index function to convert static Coulomb stress change into normalized seismicity rates, we found that the Coulomb stress-based forecasts were not significantly more effective indicators of future earthquake locations than forecasts based on smoothed seismicity (Hiemer et al., 2011). These results were likely due to Coulomb stress uncertainties, particularly near stress singularities at the ends of fault sections where many earthquakes occurred.

We evaluate time-dependent Coulomb stress earthquake forecasts based on rate-and-state friction (Toda & Enescu, 2011 and Dieterich, 1996) against a Poissonian null hypothesis, from the 10/16/1999 Hector Mine earthquake to the 4/4/2010 El Mayor Cucapah earthquake. From numerical integration, we establish a normalized seismicity rate for each day, during the target time interval, from Coulomb stress evolution and the times since all preceding source earthquakes. During each day we assume seismicity follows a Poissonian process, with expected rates defined as the rate-and-state seismicity rates. By pseudo-prospectively testing these spatiotemporal earthquake forecasts, we ascertain the role of static and quasi-static Coulomb stress change in indicating future earthquake locations and times.

High-Resolution Aftershock Distribution of 2010 Mw6.9 Yushu, China Earthquake and its Implication

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On Apr. 13, 2010, a devastating earthquake (Mw 6.9) struck the Yushu city in Qinghai, China. This was the most destructive earthquake within Tibet plateau since 2001. The mainshock ruptured the Yushu segment of the Yushu-Ganzi-Xianshuihe fault. The mainshock was preceded by an Mw4.9 foreshock, and was followed by numerous aftershocks. About three weeks after the main shock, we deployed 20 portable seismic stations encircling the surface rupture area. Most of those stations was kept running from the beginning of May to the end of November in 2010.

In this study, we performed high-resolution relocation of aftershocks recorded by both permanent and our temporary stations using the double-difference relocation algorithm. We picked both P and S arrivals for all catalog event and then obtained differential travel times from waveform cross-correlations. We relocated aftershocks using event pairs with cross-correlation coefficient no less than 0.75 and at least 6 observations. In total, we obtained high-resolution locations of ~1000 aftershocks.

Overall the aftershock sequence can be divided into three distinct groups. The first group was around the epicenter of the Mw6.0 aftershock, ~40km northwest to the main shock. Most events in this group were located at the southwest side of the fault trace, following nearly E-W direction that was consistent with the focal mechanisms of the largest aftershocks. The second group occurred along the NW-SE Yushu fault starting from the epicenter for ~30km. The third group was located near the Yushu town and was mainly to the northeast side of the rupture zone. Our next step is to use waveforms of those relocated events as templates to scan through the continuous recordings for identification of additional aftershocks. By a systematic detection/relocation of aftershocks, we hope to obtain a better understanding of the relationship among fault segmentation, mainshock rupture properties and aftershock distributions.

Velocity Contrast along Ganzi-Yushu Fault from Analysis of Fault Zone Head Waves Associated with Aftershocks of 2010 Mw6.9 Yushu, Qinghai Earthquake

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The 2010/04/13 Mw6.9 Yushu earthquake ruptured the Yushu segment of the Ganzi-Yushu Fault (GYF) in eastern Tibet, which separates Bayan Har block and Qiangtang block. After the mainshock, we deployed temporary seismic stations around the mainshock rupture zone to monitor subsequent aftershocks, and 9 stations were deployed within 5 km on the both sides of the GYF. During the 7-month deployment period, up to ~2000 aftershocks have been recorded, providing a rich data set for better imaging of detailed fault zone structures in this region.

In this study, we conduct a systematic search for fault zone head waves (FZHWs) that refract along the bimaterial fault interface. Since FZHWs spend most of their propagation paths along the fault interface with velocities on the faster side, they provide a high-resolution tool for detecting and imaging of the velocity contrast across the major crustal faults. We identify FZHW phase as low-amplitude, long-period seismic signals with polarities opposite to the direct P arrivals. In addition, we also use polarization analysis to confirm the existence of FZHW phases.

Our preliminary results have shown that several stations on the southwest side (Qiangtang block) of the GYF have recorded clear FZHWs, suggesting that the Qiangtang block has lower velocities than the opposite Bayan Har block. The corresponding velocity contrast is about 5–10%, and is coherent along the majority of the rupture zone. This observation is generally compatible with recent studies based on seismic tomography and active refraction survey in this region. The sharp velocity contrast is expected to produce a preferred rupture direction to the SE, which is consistent with the overall propagation direction of the Yushu mainshock, if the rupture speed is subshear. Our next step is to use phase arrivals of FZHWs and direct P waves into a tomographic imaging to better understand deep fault zone properties, and their relationship to earthquake rupture properties.

Geometric Complexities Along Strike-Slip Systems: New Insights on Seismic Hazards, Earthquake Behavior, and Fault System Evolution

Poster Session · Wednesday · 30 April · Cook/Arteaga

Determination of Lithosphere Rheology from Interseismic Deformation and Implications for Fault Stress Accumulation

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Models proposed to explain transient post-seismic deformation include Burgers viscoelasticity, power law creep, and/or localized Maxwell viscoelastic shear zones.

While these rheologies may be difficult to discern from surface deformation in the post-seismic period, strain accumulation models using these rheologies produce spatio-temporal patterns of interseismic deformation that can be more distinct. Moreover, strain accumulation models assuming different rheologies of the lithosphere can also result in significantly different evolutions of fault stressing rates throughout the interseismic period. This is in contrast to the commonly used elastic strain accumulation models that assume that faults are re-loaded at a constant stressing rate throughout the interseismic period. The manner in which stresses accumulate on a fault may play a critical role in seismic hazard, and thus it is useful to use geodetic observations throughout the interseismic period in order to constrain the range of plausible rheologies that may be important during the earthquake cycle. In this presentation, we demonstrate the degree to which interseismic deformation around continental strike-slip faults can be used to discern lithospheric rheology, and we examine the impact of these rheologies on the accumulation of stress on seismogenic faults.

Unraveling Enigmas in the GPS Velocity Field in the Big Bend Region of the Southern San Andreas Fault System

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The southern San Andreas Fault (SSAF) in southern California has a ~250-km-long, left-stepping (restraining) 'big bend' that deviates ~30° from its usual N40°W trend farther north and south. In this region there is ample evidence from mapping of active fault, earthquake fault plane solutions, and uplifted mountain ranges for thrust faulting and crustal shortening in the Los Angeles (LAB) and Ventura basins (VB), San Gorgonio Pass (SGP) and the Western Transverse Ranges. However, the observed Global Positioning System (GPS) velocity vector field relative to stable North America shows only minor deviation from this N40°W trend in much of southern California through the big bend region. How can this be so? Actually, the evidence for crustal shortening in the GPS field is obscured by the major effects of strain accumulation on the SSAF. Here I remove effects due to the largely locked (non-slipping) SSAF to better analyze the character and kinematics of crustal shortening. Because of uncertainties in the details of locking distribution and the along-strike variations in SSAF slip rates I explore a range of locking depths and slip distributions. Geodetic results indicate ~7 mm/yr of shortening across the SGP, ~8 mm/yr across the LAB, and ~7 mm/yr across the VB. However, rates of shortening decrease significantly to the west of the VB, being only a few mm/yr across the central and western Santa Barbara Channel portion of the western Transverse Ranges.

Fault Interaction in the San Gorgonio Pass Region of the San Andreas Fault, Southern California

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The San Gorgonio Pass (SGP) region marks the SE extent of the big bend in the San Andreas Fault (SAF). Recent research has focused on the effect of fault-strand complexity on through-going rupture along the SAF through the SGP region. In spite of this attention, many questions remain unanswered. We present recent geologic mapping and geomorphic analysis to address some of the outstanding issues. Middle-Pleistocene deposits are not offset by dextral slip along the Mission Creek fault strand. However, deposits of this age are cut by the Mill Creek fault strand, constraining the relative timing of the most recent slip along these two SAF strands. The Mill Creek strand is overlain by unfaulted younger deposits, likely late Pleistocene and Holocene in age, indicating no rupture has occurred along this strand in this time interval. Most recently, slip along the SAF in the SGP has shifted to the San Bernardino strand, to the NW of SGP, and the Garnet Hill and Banning strands of the SAF, to the SE of the SGP. Although the San Bernardino strand is not clearly connected at the surface through the SGP to the Garnet Hill or Banning strands, they may be linked at depth through the contractional San Gorgonio Pass Fault. The Banning-Garnet Hill-San Bernardino strand configuration is somewhat puzzling because it is less optimally oriented to accommodate dextral slip, than is the Mill Creek strand. The SE end of the Mill Creek strand is deflected and offset ~ 1 - 1.25 km by the Pinto Mountain Fault. This offset is consistent with our observations showing no recent slip on the Mill Creek fault strand. This offset may also be the cause of the shift in SAF slip away from the otherwise well-oriented Mill Creek strand. We conclude that the Pinto Mountain Fault system has disrupted slip through the SGP by sequentially offsetting both the Mission Creek and Mill Creek SAF fault strands and causing dextral slip to shift to the Banning, Garnet Hill, and San Bernardino strands.

Paleoseismology of the Northern San Jacinto Fault Zone and Implications for Rupture across Steps in the San Andreas Fault System, Southern California

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The San Jacinto fault is one of the major plate boundary faults in southern California, and recent geologic and geodetic data suggest it accommodates about one third of the total slip across the southern San Andreas fault system. To investigate the timing of past surface ruptures over the last 2000 years, we studied the prehistoric earthquake history on the northern SJF zone as recorded in shallow sediments at Mystic Lake, an ephemeral lake that formed at the north end of a 2.25 km-wide pull-apart basin between the Claremont and Clark segments of the San Jacinto fault zone. Between 2009 and 2013, we excavated nine trenches across the Claremont fault where it crosses through the north end of Mystic Lake. These trenches exposed evidence for 15 ground-rupturing earthquakes over the past 3700 years, with 12 of these occurring in the last 2000 years. 118 radiocarbon dates were used to determine the earthquake history recorded at the site.

We compared the timing of events at Mystic Lake to the earthquake records at the Hog Lake site on the Clark fault to the south, and the Wrightwood site on the San Andreas fault to the north to evaluate the possibility and frequency of rupture across step-overs at both ends of the Claremont fault. At least six of the 12 earthquakes that occurred in the last 2000 years at the Mystic Lake site overlap in time with earthquakes at Hog Lake, suggesting that both the Claremont and Clark faults may rupture together in some large events. Between Mystic Lake and Wrightwood, four of nine earthquakes in the past 1500 years overlap in time, suggesting that some events may also have ruptured through the step-over between the northern end of the Claremont fault and the San Andreas fault. However, there are no events at Mystic Lake that overlap with both the Hog Lake and Wrightwood records, so we consider it unlikely that any earthquakes have ruptured across both ends of the Claremont fault in very large, multi-fault cascade events.

Rupture and Ground Motion Models on the Claremont-Casa Loma Stepover of the San Jacinto Fault, Incorporating Realistically Complex Initial Conditions

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The stepover between the Claremont and Casa Loma strands of the San Jacinto Fault in southern California is a major discontinuity within a complex fault zone. This extensional stepover has an average of 4 km separation between the strands over an overlap length of 25 km. A primary question is whether rupture can jump between the Claremont and Casa Loma in one event. This region poses other questions about the dynamics of complex faults – in particular, whether small-scale geometrical complexity, contrasts in velocity structure, and heterogeneous initial stresses can control rupture behavior as much as the large stepover can, and how all of these factors contribute to ground motion. We use the 3D finite element method to conduct dynamic rupture models on a complex parameterization of this stepover. We implement fault geometry based on field mapping literature, material properties from the SCEC Community Velocity Model, a regional stress orientation taken from seismicity relocation literature, and several stochastic shear stress distributions. The stress field that arises from the combination of regional and stochastic stresses and fault geometry is the primary control on rupture extent. The contrast between high and low shear stress patches, rather than the magnitude of the stresses, determines the strength of a barrier. Greater contrast and smaller patches of high shear stress produce shorter ruptures. In most of our models, this stress pattern prevents rupture from reaching the end of either fault strand and having to negotiate the stepover. Smaller events that do not always reach the surface are consistent with historical behavior on the San Jacinto Fault. The complex velocity structure has more effect on ground motion distribution and intensity than on rupture extent. We find that the Claremont strand is more favorable for longer ruptures than the Casa Loma strand, and that the strongest ground motions are concentrated in the San Bernardino basin.

Geometric Complexities of Hosgri Fault Zone Offshore Point Sal, Central Coastal California

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As part of the Central Coastal California Seismic Imaging Project, marine seismic-reflection imaging data were acquired across the Hosgri Fault Zone (HFZ) offshore Point Sal in 2011 and 2012 using a state-of-the-art high-resolution 3D low-energy seismic survey system. Seismic-reflection profiles, 3D volumes and time slices were used to map detailed structural geometry within a 6-degree restraining bend in the

fault zone. High resolution 3D seismic imaging of faults, folds, and paleochannels also allowed identification of piercing points for estimating Quaternary slip-rates on the HFZ.

Discrete zones of deformation, including numerous conjugate, oblique reverse, and normal faults bounded by three primary strike-slip fault strands were recognized. A fault-bounded central block has been uplifted and folded into a broad, 1,200-m wide anticline, which is bisected by the Central strand of the HFZ. An abrupt change in the strike of the HFZ occurs near the intersection of the Lion's Head fault, which forms the southern boundary of the rigid Casmalia/Point Sal Block that impinges upon the HFZ from the east. This block convergence appears to have resulted in bending of the HFZ with resultant transpressive uplift and complex structural slivering. Transfer of slip from the older, indented HFZ Eastern fault strand to the younger and straighter Central and Western fault strands is suggested, and is consistent with recent structural models for strike-slip fault systems. Other geometric complexities of the three primary strike-slip faults, as well as numerous secondary, subsidiary faults provide insights into fault system evolution through time.

Newly Acquired 2D and 3D Multichannel Seismic Datasets from the Inner California Borderlands Yield New Constraints on the Timing and Style of Recent Deformation

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Marine stratigraphy in the Inner California Borderlands (ICB) records several episodes of deformation, ranging from large-scale extension and rotation to dextral strike-slip deformation. Although the San Andreas Fault and other faults onshore accommodate ~85% of the relative plate motion, geodetic surveys indicate that fault structures offshore accommodate 6–8 mm/yr of dextral motion. Proposed models to explain modern ICB deformation include the reactivation of detachment faults such as the Oceanside blind thrust and/or compressional and extensional step-overs within strike-slip fault systems. However, the available seismic imagery has lacked the resolution and distribution to define the style and timing of deformation in the ICB.

In late 2013, scientists from the Scripps and UNR conducted three low-energy multichannel seismic (MCS) and multibeam surveys to characterize fault architecture and timing in the ICB. We acquired ~4500 line-km of high-resolution, regional 2D seismic reflection data using sparker and boomer sources and two 3D seismic volumes covering a total surface area of 100 km2 using a 14 streamer, 81.25-m-wide P-Cable system. The new datasets image deformation along the Newport Inglewood/Rose Canyon, Coronado Bank, San Diego Trough, Palos Verdes, and San Pedro fault zones, and on the San Mateo, San Onofre, and Carlsbad trends. These data complement 50 lines of deeper reprocessed legacy MCS reflection data and shallow high-resolution CHIRP imagery collected by scientists at Scripps.

We will present the first processed images from the new 2D and 3D datasets. We use a sequence stratigraphic approach to interpret the tectonic evolution and recent history of fault motion in the ICB. These data show highly deformed pop-up structures corresponding to left steps in faulting and extensional basins corresponding to right steps in faulting, supporting the model that modern ICB deformation is best explained by step-overs in a dextral strike-slip fault system.

Aftershocks Following the January 5th 2013 Queen Charlotte-Fairweather Fault Earthquake near Craig, Alaska from Offshore Seismic Observations

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We present results from a rapid-response ocean bottom seismometer (OBS) experiment that recorded aftershock activity on the Queen Charlotte-Fairweather (QC-F) fault following the Mw 7.5 earthquake on January 5th 2013 near Craig, Alaska. The Craig earthquake followed a Mw 7.8 thrust event that occurred in October 2012, ~400 km to the south, west of Haida Gwaii, British Columbia. Although the QC-F is a major plate boundary fault, little is known about the regional fault structure, interseismic coupling, and rheological controls on the depth distribution of seismic slip along the continent-ocean transform. Here we present data from the first-ever offshore seismometer deployment along the northern segment of the QC-F system. The seismic array consisted of 10 GeoPro short-period OBS from the University of Texas Institute for Geophysics that recorded ~3 weeks of aftershock activity in April-May, 2013. The sensors were deployed and recovered with help from the US Coast Guard. Combining high-quality local OBS recordings with land-based seismic observations from Alaska Earthquake Information Center (AEIC) stations to the east, we present precise aftershock locations and depths that help characterize fault zone architecture along the northern QC-F. More than 500 aftershocks with magnitudes <1.0 were recorded during the OBS deployment, located along a 60-km-long section of the fault. Although moment tensor solutions indicate that the January 5th mainshock exhibited slip consistent with strike-slip Pacific-North America plate motions, aftershock focal mechanisms indicate some interaction with neighboring faults, such as the Chatham Straight fault that extends southeast of Baranof Island. Evidence for activity on branching faults is also supported by the relocated distribution of aftershocks. This new OBS dataset illuminates the geometry of the transform boundary along the northern section of the QC-F system and helps define recent large rupture segmentation.

Quaternary Crustal Deformation at the Apex of the Mount McKinley Restraining Bend of the Denali Fault, Alaska

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The tallest mountain in North America, Mount McKinley (~6,000 m), sits on the inside of a major restraining bend on the active, right-lateral Denali fault. Opposite this massive peak, on the outside of the restraining bend, is the Peters Dome foothills that are low elevation (~2500 m) and confined to a narrow zone along the Denali fault. Because the style and rate of fault deformation provides critical insight into the evolution of the restraining bend, we focus on defining the occurrence and characteristics of Quaternary fault-related deformation across the north side of the Mount McKinley restraining bend. We performed surficial and neotectonic mapping along the foothills to define active faulting and deformed landforms. Topographic profiles and cosmogenic nuclide exposure and burial dating provide preliminary controls on fault slip rates. Major faults are near-vertical dip-slip faults east of the apex of the bend and the faults to the west are SE-dipping thrust faults that parallel the Denali fault. Modeling the active faults with the regional seismicity suggests that the principle stress axes rotate significantly across the restraining bend. The variation in strain accommodation along the foothills highlight how displacement on subsidiary faults are accommodating the evolution of the restraining bend in this highly strain partitioned system. The Holocene thrust faults and increase in background seismicity to the west of bend supports westward migration of the bend being accommodated by shortening on the thrust faults.

Insight into the Evolution of the Mount McKinley Restraining Bend Through Thermochronology: Long-Term Controls on Slip Distribution

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Geometric complexities are a ubiquitous feature of major strike-slip faults and present complex seismic hazard potential. Given that the maturity of a fault feature strongly affects slip distribution, surface slip localization, and earthquake behavior (Dolan and Haravitch, 2014); a better understanding of the evolution of these features is warranted. The Mount McKinley restraining bend of the Denali fault in Alaska exists as part of a strain-partitioned transpressional system and offers a natural laboratory for investigating how restraining bends may evolve. Mount McKinley (6,194 m) is south of the Denali fault on the inside of an abrupt ~17 degree bend. We apply AFT dating and thermal modeling to samples collected on both sides of the Mount McKinley restraining bend combined with geomorphological observations to constrain both the restraining bend initiation and evolution. AFT cooling ages from samples on both sides of the Denali fault, range from ~8 Ma to ~2 Ma. Track length distributions indicate all samples cooled quickly at the time of AFT closure. This preliminary data suggest a pattern of AFT ages younging to the west. One implication of this trend is that the Mount McKinley restraining bend may be migrating to the west at a long term rate of 2 km/Ma; this rate is less than half of the modern Denali fault slip rate. Although glacier coverage of most of the Denali fault trace in the restraining bend precludes us from developing a paleoearthquake rupture history, we can use the slip rate decrease through the restraining bend

and the conversion of horizontal motion to vertical displacement to constrain possible long-term trends in earthquake distribution. Integrating structural analysis of active faults and will allow us to develop robust models for the evolution of the Mount McKinley restraining bend system, assist with a long standing paleo-slip rate controversy, regional seismic hazard assessment, and provide a geological test case for analog experiments.

Analog Modeling of Restraining Bends: A Study of Strike-Slip Fault Evolution

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Restraining bends migrate and evolve over time, by propagation of new faults and abandonment of faults. Such processes are poorly constrained in space and time, leaving open questions about how strike-slip faults interact over geologic time. Scaled analog modeling using wet kaolin allows our team to make qualitative observations and quantitative analyses about restraining bend evolution. We document fault initiation and abandonment to see how restraining bends overcome initial mechanical inefficiencies. Deformation is captured in photographs later analyzed using Particle Image Velocimetry, a particle tracking software. Restraining bends within the claybox grow oblique-slip faults outboard of the initial restraining segment on one or both sides of the restraining bend. These new faults often link with the pre-cut faults. We quantify the evolving mechanical efficiency of the fault systems as a ratio of measured fault slip per image to applied plate displacement (0.5mm/minute). At the start of fault slip, the efficiency correlates to restraining bend angle; shallower restraining bends are initially more efficient. Restraining bends with angles greater than 20 degrees have about the same initial efficiency. Restraining bends with higher angles begin inefficient, but efficiency increases as new faults propagate and link with the existing. Regardless of kink angle, all restraining bends have roughly equal efficiency (85%) after 55 mm applied displacement. We examine the Denali strike-slip system in the claybox with 13 and 17 degree kink angle restraining bends; such models resemble current relative topography distribution and surface fault traces within the Alaska Range. Both analog and crustal restraining bends may be inefficient structures along otherwise efficient strike-slip fault systems. Similarly, faults overcome such inefficiencies by abandoning high angle, moderately efficient structures in favor of propagating new oblique-slip faults.

Pillars of Simulation: Seismic Velocity and Material Models

Poster Session · Wednesday · 30 April · Cook/Arteaga

UCVM: Open Source Software Framework for 3D Seismic Velocity Models

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Three-dimensional (3D) seismic velocity models describe earth properties such as Vs, Vp, and density, and provide fundamental input data to ground motion simulations, in the form of structured, or unstructured, meshes. Multiple alternative 3D seismic velocity models are available for California, and 3D models for other parts of the United States and Europe have been developed. In order to compare, and evaluate 3D velocity models, researchers need standardized ways to query alternative models, and build meshes used for ground motion simulations. The Unified Community Velocity Model (UCVM) software is an open source framework designed to provide a consistent way to interact with alternative seismic velocity models.

UCVM includes many software tools to help researchers better understand the effects of velocity models on ground motion simulations. UCVM can be used to generate large-scale meshes for use in high-frequency 3D wave propagation simulations. It can generate Cartesian meshes, e-trees, and it can output meshes in NetCDF format. The UCVM code is very scalable; as one example, it was used to generate a 250GB e-tree that was used in a 4Hz Chino Hills wave propagation simulation.

UCVM supports: multiple California community velocity models (although there is no intrinsic dependency upon California); sea-level or ground-level vertical references; an optional Vs-30 derived geotechnical layer; and the introduction of small-scale heterogeneities into velocity models for use in higher frequency simulations. UCVM can also be used to help visualize meshes, by exporting them seamlessly to existing software tools, such as IDV.

Recently, UCVM has been used to deliver and evaluate tomography-based improvements to SCEC's CVM-S4 southern California 3D velocity model. The resulting model (CVM-S4.26) combines the original model, and perturbation-based improvements for output in arbitrary resolution meshes.

Two-Station Micro-Tremor Measurements to Detect the Depth to Bedrock in Sultan, Washington

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We performed a passive surface wave method at two sites in the Cherry Creek fault zone (CCFZ) in Sultan, Washington to detect the depth to bedrock below Quaternary deposits. Gravity, structural, subsurface and earthquake data suggests that the main strand of the CCFZ that strikes NNE is a left- lateral strike slip fault zone with a substantial eastside-up component of offset. The purpose of the study is to confirm a geological structural interpretation of the fault suggested from existing geological information (Dragovich et al., 2013). The passive surface wave method was performed at two sites with approximately 500 m separation at both east and west sides of the CCFZ. We used two-station microtremor array measurements to obtain dispersion curves. At each site, one seismograph was established at a fixed location and acquired microtremor data for the duration (several hours) of the survey. A second one acquired data using variable separations from the fixed site ranging from 10 to 659 m and 10 to 400 m at east and side west of the CCFZ, respectively. A spatial autocorrelation method was used to calculate phase velocities from the data and an inversion using a genetic algorithm estimated S-wave velocity (Vs) profiles from dispersion curves. The phase velocities were determined in a frequency range between 0.8 and 10 Hz. The phase velocities at the east side are higher than for the west side in a frequency range below 2 Hz. Vs profiles obtained by the inversion shows that the approximate depth to bedrock ($Vs > 700$ to 750 m/s) at the east side is 150 m and the west side is 260 m. The investigation results confirm gravity and some borehole data presented in the existing report indicating that the main strand of the CCFA is spatially coincident with distinct shallowing in bedrock in the subsurface in the Skykomish River area. The result appears to be a bedrock ridge on and east of the main fault strand that might be the result of Pleistocene and older oblique offset.

Detection of Shallow Crustal Discontinuities from High-Frequency Waveforms of Local Microearthquakes

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Determination of seismic velocity model within the crust is usually inferred from active seismic investigations, reflection and refraction imaging. Passive seismic investigation focused on microseismic or local sources has an advantage since it typically handles large amount of data ideal for stacking, sources are usually far from the shallowest structure so waveforms are rather simple, and data acquisition is not expensive. The standard microseismic monitoring is prevalently used for retrieving information on seismic source parameters. However, knowledge of a detailed structure of seismoactive region is essential for all advanced studies and can find broad applications in crustal studies, exploration seismics, mining, and natural microseismicity.

The method is tested on waveforms of local microearthquakes from West Bohemia/Vogtland region recorded by network of 22 three-component seismic stations. We focus on high-frequency PS and SP converted waves generated at shallow interfaces at depths between 2 and 5 km. Apart from velocity contrasts, the amplitudes of converted waves are significantly affected by source-receiver geometry and focal mechanisms of the earthquakes. This observation complicates the analysis, being absent in processing of standard active experiments with sources of rather uniform radiation. The strong dependence of reflection/conversion amplitudes on focal mechanisms and source-receiver geometry is confirmed by synthetic tests, which reveal preferential azimuths suitable for interpretation of data. We developed a new multi-azimuthal approach for data processing, followed by data alignment and stacking, analysis of reflection/transmission coefficients, synthetic modeling of full waveforms using the discrete wave number method, and the grid search algorithm as the robust inversion. Good azimuthal coverage of stations and proper attention paid to radiation patterns enable to retrieve even the topography of interfaces.

Detailed Crustal Structure of the North China and its Implication for Seismic Activity

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Since the Mesozoic-Cenozoic era the North China Craton has experienced an important tectonic transition which gave rise to complicated crustal structure and strong earthquake activity. Based on the large-scale surface gravity data, we studied the detailed crustal structure and seismogenic mechanism of the North China. The results indicate that the North China presents typical characteristics of adjoining depression and uplift, alternating basins and hills, inhomogeneous density and also great differences in crustal structure and Moho topography. The upper and middle crustal structures are dominated by the NNE-striking tectonic units, with many faults cut down to the middle crust. The lower crust is characterized by the folding-structure, with high- and low-density placed alternately from west to east, presenting lateral heterogeneous feature. Adjusted by the gravity isostasy, Moho topography of the North China fluctuates greatly. Compared with the North China Basin, crustal thickness in the Western Taihang, northern Yanshan and Luzhong areas are much thicker while those densities are lower than the North China Basin. The dominating tectonic direction of the Moho topography strikes NE to NNE and undulates alternately from west to east. Gravity anomalies in the upper and middle crusts of the mountainous areas are related to the surface topography. The epicenters are mostly concentrated in the upper and middle crusts, especially the transitional areas between the high- and low-gravity anomalies. The Tancheng earthquake in 1668, Sanhe earthquake in 1673, Tangshan earthquake in 1976, and all other seismic tectonic zones of the North China are all distributed in areas where magma moves strongly beneath the crust, which is considered to be related to the movement of the high density, unstable and heat flows along the deep passage from the uppermost and asthenosphere due to the subduction of the Pacific slab towards the Eurasian plate.

Frequency Dependent Lg Attenuation in Northeast China

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The 127 station Northeast China Extended Seismic Array (NECESSArray), previous PASSCAL experiments, GSN broadband stations, Chinese, Japanese and South Korean permanent stations provides unprecedented seismic data in Northeast China, allowing us to resolve lateral variations of Lg Q greater than or equal to 2.0°. We gathered more than six thousand Lg path-amplitudes from more than hundred crustal earthquakes. Using the reverse two-station/event method, we obtained a two-dimensional tomographic image of Lg Q with its values ranging from about 50 to 1500. A high degree of detail in the lateral variation of Lg attenuation is revealed in our tomographic image than the previous studies in the area. We also observe strong frequency dependent in attenuation. Low attenuation regions are found in the Great Xing'an, Lesser Xing'an and Songen-Zhangguangcai Ranges. Islands of low attenuation appear to be associated with granitic batholiths in the Great Xing'an Range. Attenuation is high in the Songliao, Sanjiang, Erlian Basins and Bohai Basins. The highest attenuation is found in the vicinity of the Changbaishan, Wudalianchi volcanic field, and Quaternary volcanic regions, the southern Songliao Basin, west of Erlian Basin, Bohai Basin and the Sanjiang Basin. Highly attenuating regions correlate well with regions of high heat flow and volcanism, suggesting intrinsic attenuation as the main cause of low crustal Q. Low Q regions also occur within basins with thick, unconsolidated sediments. Some of the high Lg attenuation regions, outside of the Great Xing'an Range and Songliao Basin, correlate well with the uppermost mantle low shear wave velocity anomalies, suggesting that hotter uppermost mantle also contribute to crustal attenuation.

High Resolution Regional Travel-Time Tomography in South-Central Tibet: Imaging Tibetan Crust beneath the Hi-CLIMB Array

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The HiCLIMB Phase II broadband seismic experiment operated 133 stations along a 550 km long north-south line from the Himalayan hinterland to the central Tibetan Plateau and a 350 × 350 km sub-array within southern Tibet. Station spacing was approximately 8 km along the line and 50 km within the sub-array. The experiment spanned the Himalayan range, Lhasa Block, Qiangtang Block and crossed the Yarlung Tsangpo Suture (YTS) and the Banggong-Nujiang Suture (BNS). From June 2004 to August 2005, over 22,500 local and regional seismic events were recorded and located throughout the south-central Tibetan Plateau based on automated arrival time picks. This dataset provides an opportunity to jointly invert for crust and upper mantle velocity structure along with earthquake locations using P and S waves. We use a subset of 5,900 best-recorded local events containing over 200,000 P and 90,000 S wave arrivals to conduct the inversion. Our preliminary results indicate well resolved velocities in the upper mantle and upper to middle crust, 0–50 km depth. In the upper crust, 0–20 km, we observe east-west striking low Vp zones associated with the BNS and YNS. These velocity anomalies are not present at depth, suggesting the suture zones do not affect the velocity structure below the shallow crust. Within the Lhasa Block Vp values increase abruptly from south to north around 31°N in the mid-crust, 30–50 km depth. Low Vp values in the southern Lhasa Block and northern Himalayas match with receiver function data and could indicate partial melt or the presence of pore fluids in the middle crust. In the northern Lhasa Block a thin, high Vp layer extends from 31°N to 34°N past the BNS into the Qiangtang Block at 30 to 40 km depth. This layer has not previously been mapped and its composition is being determined. In the upper mantle an east-west velocity gradient is present with high Vp values to the east beneath the YTS and low Vp values to the west within the Qiangtang Block.

Sn Attenuation in Northeast China

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Northeast China is a generally active continental region which is controlled by Pacific plate subduction and India-Eurasia collision. In this study of uppermost mantle seismic wave attenuation, we use the regional high frequency seismic phase Sn to measure mantle lid shear wave Q. We have used data from the three-component broadband seismograms recorded by the Northeast China Extended Seismic Array (NECESSArray). We collected waveform data recorded by 127 stations from 140 earthquakes within a rectangular region from 30°N to 60°N in latitude, 100°E to 145°E in longitude.

Models of Sn Q are calculated by applying both two-station method (TSM) and reverse two-station method (RTM). The RTM is more accurate and eliminates the site responses and crustal contribution to Sn attenuation. The site effect is then estimated form comparing the results from these two methods.

In general, the inversion results show high Q values lie in Songliao Basin, indicating relatively low temperature for the uppermost mantle. We can roughly divide the Q_0 values into four regions: low ($Q_0 < 400$), medium low ($400 < Q_0 < 800$), medium high ($800 < Q_0 < 1200$), and high ($Q_0 > 1400$). We observed low Q_0 in Xilinhot block, Songnen block, eastern Zhangguangcailing block and Yanji block which are part of Songnen unit, medium low Q_0 in Okhotsk belt, medium high Q_0 in northern Songliao basin, and high Q_0 in southern Songliao basin and western Zhanggaungcailing block. The basins are characterized by high Sn Q_0 values. The borders between high Q_0 and low Q_0 are mostly along the active faults. Resolution test using checkerboard shows good resolution at scale of 2° × 2° within most of the study area.

Mechanisms of Postseismic Deformation Following the 2010 M=7.2 El Mayor-Cucapah Earthquake

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The Salton Trough is an ideal site in which to use postseismic deformation to study the rheology of the crust and upper mantle. In this region, lithospheric thinning has brought the low-viscosity asthenosphere up to within <50 km of the surface, high surface heat flow implies low viscosities throughout the thin lithosphere, and the transform component of relative plate motion produces large

strike-slip earthquakes that impart large stress changes to this low-viscosity structure, likely inducing significant postseismic deformation. The 2010 Mw=7.2 El Mayor-Cucapah earthquake was the largest in the Salton Trough since at least 1892 and the postseismic deformation following this earthquake may provide insights into rheology at depth that are difficult to extract elsewhere. Three-year postseismic displacement timeseries extracted at UNAVCO GPS stations show four key attributes: 1) the Imperial Valley experienced ~2 cm of uplift in both coseismic and postseismic deformation; 2) significant westward displacement occurred in the Peninsular Ranges, suggesting a long-wavelength mechanism; 3) near-field timeseries show a rapid deformation signal in the first year after the mainshock; and 4) that signal is followed by a sustained signal that is still active at the time of writing. Forward modeling of stress-driven deformation reveals that the uplift in the Imperial Valley and the large displacements in the Peninsular Ranges are best fit to Newtonian viscoelastic relaxation in a low-viscosity asthenosphere with geometry matching the regional lithosphere-asthenosphere boundary inferred from receiver functions. The temporal signal in the near field can be fit to a variety of plausible mechanisms and rheologies but, among them, is well fit to a combination of deep afterslip and Newtonian viscoelastic relaxation in the lower crust, both plausible deformation mechanisms for a large strike-slip earthquake in a high-heat-flow region.

Separation of the Earthquake Tomography Inverse Problem to Refine Hypocenter Locations and Tomographic Models: A Case Study from Central Oklahoma

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The tomographic inverse problem is sensitive to both the velocity anomaly distribution and hypocenter origins. By using an inversion approach to solve for both hypocenter origins and velocity structure, additional unconstrained dampening parameters must be set to run the joint inversion. Each dampening parameter has a range of reasonable values, so the more inversion parameters that must be set to run the inversion increases the ambiguity in the final model. Furthermore, since the tomographic modeling and 3D hypocenter location steps both benefit greatly from grid searching and analysis of trade-off curves, determining the range of reasonable values for each of the inversion parameters can become an increasingly difficult problem in itself as the number of dampening and model parameters increase. For these reasons, we separate the hypocenter location process from the tomographic inversion and run these steps iteratively.

The data used in this study was obtained from a deployment of 156 vertical 2-Hz geophones and 18 3-component broadband seismometers. The survey spanned 70 kilometers between two zones of increased seismicity in Central Oklahoma; the first area is the Jones earthquake swarm, and the second is the Wilzetta Fault rupture of 2011. From the eight earthquakes that were recorded, approximately 1,500 P and S travel times for direct and refracted rays were determined. These travel times were used to constrain 3D tomographic modeling using FMTomo (Rawlinson, 2006) and to locate the hypocenters in the resulting 3D tomographic model in NonLinLoc (Lomax et al., 2001). Due to the dramatic increase in earthquakes Oklahoma has seen in the last few years, the tomographic technique described here will be applied to the entire Oklahoma earthquake catalog to generate a community 3D velocity model for central Oklahoma.

Detailed Near Surface Velocity Model and Site Response of the Hayward, East San Francisco Bay Area: 2D Velocity Model Based on Active and Passive Surface Wave Methods

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We conducted active and passive shear-wave velocity (V_S) surveys at several locations along a 4 km long transect crossing the Hayward fault and extending onto the alluvial basin at the foot of the East Bay hills. At each site, three types of surveys were performed. Near-surface velocity structure was measured to depths of ~20–40 m using a 48-channel linear array with 1) a hammer source and 2) ambient noise. Deeper velocity structure was measured to depths as great as ~2000 m using a two-station SPAC (spatial autocorrelation) method. Data recorded using the three methods were then combined to produce a single dispersion curve for each site. Each dispersion curve was inverted to provide a V_S profile. The maximum depth at which velocity could be measured varied from ~200 to 2000 m, depending on the site.

V_S profiles show signigicant lateral variations across the Hayward fault. A gabbroic site in the uplifted East Bay hills has a thin weathered zone overlying basement; V_S exceeds 1500 m/s at a depth of 250 m. Valley floor sites within 1–2 km of the Hayward fault have a thicker near-surface layer with slower velocities consistent with sedimentary materials; V_S in the upper 100 m is generally less than 500 m/s, gradually increasing to 1250 m/s at a depth of 450 m.

Site Response: From Site-Specific Analyses to Predictive Models Around the Globe

Poster Session · Wednesday · 30 April · Cook/Arteaga

Detailed Near Surface Velocity Model and Site Response of the Hayward, East San Francisco Bay Area: Seismic Observation of a Building Implosion and its Interpretation from Site Response Point of View

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A twelve-story building at California State University, East Bay, in Hayward, CA was demolished by implosion in August, 2013. The building was located ~300 m away from the Hayward Fault and seismic ground motion induced by the implosion was recorded to study velocity structure across the Hayward Fault. We deployed five sets of three-component broadband accelerometers across the Hayward Fault and recorded ground motion induced by the implosion. Accelerometers were placed along a line oriented perpendicular to the Hayward Fault with a spacing of approximately 800 m at distances ranging from 800 to 4000 m from the building. The implosion was clearly observed at all stations. The ground motion induced by the implosion lasted ~15 s and propagated with apparent velocity of ~400 m/s. Maximum acceleration was ~4.4 cm/s^2 at a distance of 800 m from the building and ~0.3 cm/s^2 at a distance of 4000 m. Spectra of all stations are basically flat from 0.5 Hz to 50 Hz, with no obvious peak. The spectrum from each station was divided by the spectrum of the station closest to the building to estimate site amplification. Resultant horizontal spectral ratios clearly show peaks at 1.5 Hz. A representative S-wave velocity cross section was constructed based on the active and passive surface wave methods and theoretical ground motion was calculated using a 2D viscoelastic finite-difference method. The theoretical ground motion shows a clear peak frequency at ~1 Hz and it is generally consistent with the observed implosion record. The S-wave velocity model constructed by the surface wave methods and the observation of the building implosion implies that the low frequency component of ground motion may be locally amplified on the west side of the Hayward Fault because of the effect of two-dimensional structure.

Effect of Site Models on Standard Deviation of GMPEs and Fundamental Site Frequency as a New Complementary Site Parameter

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For pan-European region, Akkar et al. (2013; ASB13) proposed the next generation ground-motion prediction equations (GMPEs). When compared to previous GMPEs for the region, ASB13 developed the equations with a nonlinear site model that makes use of VS30 and PGArock. In this study, with the same dataset, we performed regressions to investigate the effect of different site models (i.e., generic soil classes, linear and nonlinear site models) on sigma of GMPEs. Using either linear or nonlinear site models in predictive equations result in significant decrease in sigma with respect to ones with generic site classes. The change of sigma between linear and nonlinear site models are quite negligible in long periods; however, in low VS30 range at short periods where soil nonlinearity is observed, the difference becomes more visible (on average the reduction is about 5%). In addition, additional site parameters (i.e., depth-to-rock, Z1 and fundamental site frequency, F0) to improve ASB13 were investigated. Both parameters are effective in reduction of sigma at longer periods (T>0.65s). Based on our preliminary results, the efficiency of F0 is more than Z1.

Empirical Assessment of Site Effects in Low Seismicity Areas

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In case of unfavorable geological and geomorphological local features, site effects can significantly amplify ground motions. It is possible to quantify these site effects

by numerical simulation with a given seismic scenario (source location, magnitude . . .) and a description of geological, geophysical and geotechnical environment. However, these simulations cannot alone address the whole issue of site effect evaluation. Indeed, the geological features will probably never be described with the required resolution to characterize the seismic motion up to high frequency. It is therefore essential to complete the simulations with seismic recordings of real earthquakes. Such "empirical" approaches allow: a/ to access Standard Spectral Ratio (SSR) measurement or other quantification of the site-specific transfer function (coda, duration, . . .), b/ to consider the use of methods by empirical Green's functions, c/ to evaluate the attenuation of high frequency of seismic signals (characterized by the "kappa" parameter). While these approaches seem readily available in areas of high seismicity (Japan, Greece, California . . .), where the data are both numerous and correspond to earthquakes of moderate to high magnitude, they are more difficult to implement in low seismicity areas, as in metropolitan France. Indeed, earthquakes we can record in these area are few and correspond to remote earthquakes (earthquakes with medium or high magnitude but far from the site of interest), or regional and local earthquakes, but with low to moderate magnitude.

We present the available data set for a site located in Provence, South East of France, over a 2 years period (2012–2013). We discuss the potential use of these data according to the distance of valuable earthquakes (local, regional or distant earthquakes) with respect to the different kind of analyses (SSR, coda, kappa. . .) and local anthropic noise.

Rock and Stiff-Soil Site Amplification: Dependency on V_{S30} and kappa (κ_0)

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A ground-motion prediction equation (GMPE) specific to rock and stiff-soil sites is derived using seismic motion recorded on high V_{S30} sites in Japan. This GMPE applies to events with $4.5 \leq \mathrm{Mw} \leq 6.9$ and V_{S30} ranging from 500 to 1500 m/s (stiff-soil to rock sites). The empirical site coefficients obtained and the comparison with the simulated site functions show that seismic motion on rock and stiff-soil sites does not depend only on V_{S30}, but also on the high-frequency attenuation site properties (κ_0). The effects of the site-specific κ_0 on site amplification are analyzed using stochastic simulations, with the need to take into account both of these parameters for rock-site adjustments. Adding the site-specific κ_0 into the GMPEs thus appears to be essential in future work. The rock-site stochastic ground-motion simulations show that the site-specific κ_0 controls the frequency corresponding to the maximum response spectral acceleration ($f_{amp}1$). This observation is used to link the peak of the response spectral shape to κ_0 in this specific Japanese dataset and then to add the effects of high-frequency attenuation into the previous GMPE from the peak ground acceleration and up to periods of 0.2 s. The inclusion of κ_0 allows the observed bias to be corrected for the intraevent residuals and thus reduces sigma. However, this κ_0 determination is limited to a minimum number of rock-site records with $Mw \geq 4.5$ and to distances of less than 50 km.

Site Response in Western Washington from Specral Ratios

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We compare site amplification and resonant frequencies from 3-component broadband ground motion data, strong motion data and ambient noise for locations encompassing the Seattle and Tacoma, Washington, basins. Records were acquired from the 2012 M 6.1 Vancouver Island earthquake and its M 4.5 aftershock and from the 2012 M 7.8 Queen Charlotte Islands earthquake for the comparison. Seismic stations were chosen to cover different geologic units close to Seattle and Tacoma basins and other areas in west part of Washington State. In order to determine the site amplification, we used Fourier spectral ratios of recorded horizontal ground motions, referenced to a rock site. SSR plots show a considerable amplification in in frequencies above 2Hz. As observed by others, a shift in frequency exists between the mainshock and the aftershock, which possibly is due to a non-linear response of soil sites. However this shift is not consistent in all frequencies and at sediment sites. H/V results show resonant frequencies ranging from 2Hz to 15Hz. A comparison of H/V values for noise and earthquake data suggests that the peak frequencies at each site are relatively stable, except for one of the stations. Peak frequencies likely correlate with different depths to basement. There is a good agreement between the results from this study and previous studies in the area, suggesting that ambient noise studies may provide useful information about ground motions in sedimentary basins.

Site Amplification using Generalized versus Hazard-Consistent Ground Motion: A Site-Specific Comparative Case-Study in CEUS

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In PSHA, one approach to consider the effect of local site amplification convolves amplification functions (AFs) with rock hazard curves to obtain hazard curves at the surface of the soil deposit (e.g., Bazzurro and Cornell, 2004). Magnitude (M) and distance (R) terms are usually omitted in the integral form of the convolution based on the assumption that the M and R dependencies of AFs are insignificant compared to the intensity dependency. This implies that generalized, site-independent rock motions can be used to derive the AFs. In this study, soil hazard derived using generalized rock motions is compared with that derived using hazard-consistent rock motions for a site in the CEUS. The hazard-consistent rock motions are determined based on rock hazard deaggregation at multiple annual frequencies of exceedance (AFE) and multiple oscillator frequencies. The comparison shows that the soil hazard derived from the two alternative approaches (generalized versus site-specific) are similar for most of the AFEs and oscillator frequencies. However, significant differences in soil hazard are observed for certain AFE and frequency combinations, when far and near controlling events have comparable contribution to the rock hazard. It is illustrated that the frequency content of the input rock motions for the far event and near event are significantly different, which results in larger variability in the derived AFs. This leads to larger soil hazard when the hazard-consistent motions are considered. In contrast, the soil hazard derived using generalized rock motion is smaller because the motion dependent variability in AFs is neglected. If generalized ground motion is used instead of site-specific hazard-consistent ground motion to derive site-specific AFs, the derived soil hazard may be non-conservative, depending on the rock hazard deaggregation.

Shallow and Deep Shear-wave Velocity Data for ShakeMaps, Characterizations of Earthquake Recording Station Sites and Site Response Analyses in Washington and Oregon

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Washington State Department of Natural Resources – Division of Geology and Earth Resources (WADNR-DGER) has been conducting active/passive seismic surveys to estimate shallow and deep shear-wave velocities (Vs) for strongmotion and broadband stations of the Pacific Northwest Seismic Network (PNSN) in Washington and Oregon. We used SH-refraction, Multichannel Analysis of Surface Waves (MASW) (Rayleigh and Love waves) methods to estimate shallow Vs profiles that can be used to improve ShakeMap products and seismic soil classification, both of which are inputs to HAZUS-MH Earthquake Risk analysis software. Recently, we tested passive single-station and multi-sensor Microtremor Array Measurements (MAM) to estimate Vs at depths (from 10 to 3000 meters) in Seattle, Olympia and Portland. Single-station Horizontal-to-Vertical Spectral Ratio (HVSR), and multi-sensor and 2-station microtremor arrays were used to estimate deep Vs profiles. These deep Vs profiles can be used as inputs for urban earthquake hazard assessments and individual building evaluations (i.e., schools, hospitals, and other essential structures), both within and outside of sedimentary basins. We will present examples of Vs data generated using these practical and cost-effective survey methods used for evaluation of individual buildings at schools in Washington, site response analyses at PNSN stations inside and outside the basin areas in Seattle and Portland. Finally, we will present examples of seismic site characterization results used for HAZUS-MH earthquake damage evaluations of individual school buildings in Washington, and development of a subsurface database for the PNSN strongmotion station sites in Washington and Oregon. Our effort of building shallow and deep Vs velocity database correlated with available borehole information will help significantly improve ShakeMap products, urban hazard mapping in Pacific Northwest, and understanding site effects on ground motions at the PNSN stations.

Computation of H/V Spectral Ratios at Sites with Strong Lateral Heterogeneity using Diffuse Field Theory and IBEM

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It is well known that horizontal-to-vertical H/V spectral ratios of microtremors are useful to identify the dominant shear frequency. In some cases H/V is considered to be either the S wave amplification or the Rayleigh wave ellipticity although there are little theoretical basis to support these assertions.

It has been recently proposed a theory for microtremor H/V spectral ratios based on the diffuse field assumption (Sanchez-Sesma et al., 2011). In this theory H/V corresponds to the square root of the ratio of the sum of horizontal energy densities with respect to the vertical one. The directional energy densities are proportional to the imaginary parts of the corresponding components of Green's tensor when both source and receiver are the same point.

For horizontally layered medium, we can easily calculate the theoretical Green function. Thus, by observing microtremors we can assess the underground structure below by using the theoretical point source solution. On the other hand, for a laterally heterogeneous structure, the horizontal responses are different. In that case, to simulate microtremor H/V spectral ratios, a numerical approach is needed.

In this communication the 3D indirect boundary element method (IBEM) is used to study laterally heterogeneous elastic layers over a half-space. In order to overcome the singularity within the IBEM the reference solutions correspond to the classical half-space problems by Lamb (1904) and Chao (1960), for normal and tangential loads, respectively. Alternatively, for irregularities and inclusions over an elastic half-space we can gather a set of incoming P, SV, SH and Rayleigh plane waves that insures the illumination that corresponds to a diffuse field. With these plane waves as excitation to 3D configurations and using IBEM to compute the response, the autocorrelations can then be easily obtained. A large number of cases are analyzed for which we compute the H/V in 3D settings.

Validation of Dynamic Site Soil Profile at the Central United States Seismic Observatory, New Madrid Seismic Zone

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Understanding near-surface site effects is a key component for reliably estimating seismic hazard, especially at sites located on unlithified surficial materials, which can present a significant vulnerability for engineered structures. The New Madrid seismic zone, which lies within the northern Mississippi Embayment, contains thick (up to 1 km) sequences of unlithified sediments overlying Paleozoic bedrock. We use waveforms from twenty far-field earthquakes with magnitudes ranging between 2.5 and 4.7, which were recorded at the Central United States Seismic Observatory (CUSSO), a vertical seismic array in the Mississippi Embayment, to validate the site's proposed dynamic soil model. CUSSO consists of broadband and strong-motion sensors in the bedrock, and at various shallower depths that correspond with the major impedance boundaries within the 585m-thick soil overburden, including the free surface. We numerically propagate observed bedrock motions through the CUSSO soil profile (transfer function) and compare the results, in terms of both peak acceleration and amplitude spectra, to the recorded surface observations. The predicted and observed surface motions are consistent for the recorded events, and provide a preliminary validation for the dynamic site soil profile.

Infinite Wedge Revisited: Scattering of Plane Waves by Wedge Topographic Features

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The scattering of seismic waves by elastic wedges has been a topic of interest in seismology and geophysics for many decades. Analytical, semi-analytical, experimental and numerical studies on idealized wedges have repeatedly provided insight into the seismic behavior of continental margins, mountain roots and crustal discontinuities. Published results have primarily focused on incident Rayleigh waves, and to a lesser extent on out-of-plane polarized body SH waves. However, there exist very few studies on the scattering of in-plane polarized (P and SV) waves by wedge topographic features, an idealized problem with clear connection to the understanding and parameterization of topographic amplification of seismic ground motion. We here use explicit finite differences to simulate SV wave propagation in an infinite wedge. Setting the edge length greater than 20λ, where λ is the wavelength of incoming wave, we create a spatiotemporal distance that adequately separates the effect of direct incident waves – reflection and transmission through wedge sides, and diffraction by the vertex – from the waves generated by spurious diffraction. This separation overcomes the limitations of previous analytical studies, and enables us to compute the normalized amplification factors at the vertex for a wide range of internal angles. Our results are compared to previous experimental results, and analytical models such as the graphical solution by Sanchez-Sesma (1990) for two diffraction free angles of 90° and 120°.

Induced Seismicity

Oral Session · Thursday · 8:30 AM · 1 May · Room 1 Session
Chairs: Ivan Wong, Justin Rubinstein and Thomas Braun

Factors that Enhance the Likelihood of Fluid Injection-Induced Earthquakes Large Enough to be Felt

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Felt earthquakes induced by fluid injection at depth typically are magnitude 2.5 and larger. Fluid injection operations that induce felt earthquakes include geologic disposal of wastewater, development of enhanced geothermal systems (EGS), and, on rare occasions, hydraulic fracturing. Of these three activities, wastewater disposal predominates both in terms of volumes of injected liquid and earthquake size, with magnitudes sometimes exceeding 5. Thus, total injected volume appears to be an important factor in the seismic response to injection, an observation consistent with case histories of induced earthquakes large enough to be of concern. Similarly, injection directly into crystalline basement seems to increase significantly the likelihood of felt earthquakes, as evidenced by case histories involving wastewater disposal and EGS. Another important factor is the presence of high-permeability fluid pathways that can channel the injection effects on pore pressure from the target aquifer into a fault zone, especially a fault that is well oriented for slip in the ambient stress field. Often, these faults are only revealed by the hypocenters of the induced earthquakes. The effect of injection rate is less straightforward. There is some evidence that during high-injection rate EGS stimulation earthquake rates are higher than those associated with lower-rate wastewater disposal. Assuming all other factors are equal (state of stress, appropriate fault orientation, and fluid pathways) this would suggest that the likelihood, per unit time, of a felt earthquake increases with injection rate. Given that high-rate fluid injection is typically very brief, the overall likelihood of felt earthquake being triggered by much longer operating lower-rate wells is likely higher than at high-rate wells. The available data corroborate the notion that the likelihood of induced earthquakes large enough to be felt is largely independent of injection rate.

The Curious Case of the Timpson, TX Earthquakes: Natural or Delayed Triggering?

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In May 2012, residents of the small East Texas town of Timpson began feeling earthquakes. Homes and businesses have been damaged by several events with the largest being an M=4.8. Although a nearby E-W trending fault system is mapped, this region of the U.S. is generally considered aseismic. Weston Geophysical Corp., the USGS, and Stephen F. Austin State University installed local seismic networks to monitor and better define the earthquake activity. Approximately 100 earthquakes had been detected through 2013. Additional smaller earthquakes likely occurred prior to the installation of the seismic networks. We have located the events in two main clusters south of the town of Timpson. The event epicenters indicate a linear trend that likely images a NW-SE trending fault.

As a by-product of the hydraulic fracturing and natural gas production that has increased significantly near Timpson since 2006, large volumes of brine water are produced and require disposal. Two wastewater disposal wells began operation near Timpson, TX in 2006 and a third in 2009. Total injection volumes have decreased steadily since a peak in early 2008. The epicenters for the Timpson events lie between the two primary wastewater injection wells. In verified cases of triggered seismicity from wastewater injection, the earthquakes often start within weeks or months of high-volume injection onset. If the Timpson earthquakes are being triggered by wastewater injection from nearby wells, an important question is why events were not detected or felt during the peak years of wastewater injection.

Trying to Discriminate Triggered from Natural Seismicity: Three Case Studies from Northern Italy

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Human operations near seismogenic areas rise always the question, whether they are involved in triggering local seismicity. In Central and Northern Italy anthropogenic activity like oil and gas extraction, waterlevel changes of impoundment basins and production of geothermal energy are recent examples.

We present the analysis of microseismicity observed after the rupture of the fill crest of a huge barrier lake and close to the production area of CO2. A third case study treats the two damaging earthquakes with magnitudes Mw 6.0 and 5.8 that struck the Emilia-Romagna region in the sedimentary Po Plain, on May 20th and 29th 2012. The shallow hypocentral depth (6–10 km) led to severe damage and substantial impact to the local economy, and 24 fatalities were reported. The foredeep basin in Northern Italy is bordered by two active thrust and fold belts, the Apennines and Southern Alps, and convergence between them is accommodated by buried outer thrust fronts in the Po Plain. The Emilia 2012 earthquakes, which occurred on these buried faults, were therefore considered to be caused by tectonic processes.

In the closer area to the Emilia events, at least one oil/gas field (Cavone) was exploited since 1980. Besides, small amounts of wastewater are reinjected through one of the boreholes. This raised recently concerns whether these earthquakes could have been influenced by reservoir depletion from former exploitation.

We apply a novel probabilistic discrimination method to assess the probability that the earthquakes were human triggered or possibly induced. The depletion-induced stress perturbation is modeled by means of boundary element method adapted for the nuclei of strain approach. Human- and tectonic-induced stress rates are compared using a rate and state frictional nucleation model to assess relative earthquake probabilities, a method previously tested with depletion-triggered earthquakes in the North Sea and the Northern German basin.

The Azle, Texas, Earthquake Sequence of 2013–2014: Induced or Natural?

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In early November, 2013 a sequence of locally felt earthquakes began in north-central Texas near the city of Azle, approximately 30 km northwest of Fort Worth. The sequence included eight with magnitudes − 3 by the end of 2013. These are the first earthquakes to be instrumentally detected in the area since at least 1973. Epicenters determined by the NEIC span an area 25 km in dimension, although waveform similarity suggests a more compact source region. Geocoded intensity values from area residents reported to the 'Did-You-Feel-It?' website concentrated in a limited area north of Azle. Five NetQuakes seismographs were deployed in mid-December to more accurately determine the location of the earthquakes. The improved locations pinpoint the epicentral region to lie about 8 km north of Azle. Focal depths range between 4 and 6 km, placing the earthquakes in the shallow basement. Based upon these results, we were able to revise the locations obtained for the earthquakes reported by NEIC that occurred before the local network was installed. Using differential travel times at stations located 100–300 km from the activity all of the previously scattered epicenters now fall in the same limited area as the locally recorded events. The sudden onset of the seismicity and its persistence in an area without previous activity raises the question of whether they are natural or induced. There are many producing gas wells within a few km of the earthquakes in this portion of the Barnett Shale Play. Most were drilled years before the activity began and there were no hydraulic fracturing operations in progress at the time the earthquakes occurred. The Texas Rail Road Commission data base lists several active disposal wells within several km of the earthquakes, including one that had injected 6 million m3 since 2009, located within 2–3 km of the epicenters. As of this writing it is not known if there is a connection between the waste water disposal and the earthquakes.

Characterization of an Earthquake Sequence Triggered by Hydraulic Fracturing in Harrison County, Ohio

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On Oct 2, 2013, OhioSeis and the IRIS Transportable Array (TA) stations in Ohio detected a sequence of 6 earthquakes, two as large as Mw 2.0. These events, located in Harrison County Ohio, near Clendening Lake, were followed by 4 positive (Mw 1.7–2.2) magnitude events from Oct 3 to Oct 19. A total of 10 earthquakes were located in a region where no prior seismicity was observed. HypoDD was used with cross correlation to invert for double difference locations resulting in a linear E-W trending cluster located ∼800m to the West of 3 wells undergoing hydraulic fracturing at the time. To find lower magnitude events, a master event cross correlation technique was used to detect similar signals on the closest TA station (O53A ∼4km away). Using one Mw 2.0 event on Oct 2 as the template event, 298 matching signals were found (with X-corr coeff > 0.85) as far back as Sept 8. The same technique was applied back to Dec 2012 but revealed no other matches. During this sequence, hydraulic fracturing was performed from Sept 7 to Oct 6 on 3 wells − 4.0 km SW of O53A. Using the same technique, an additional 190 earthquakes were observed between Oct 2 and Dec 13, 2013. Moment magnitudes for all signal detections were determined using scaling to the template event and ranged from -0.77 to 2.2 with a G-R b-value for the earthquakes of 0.88 ± 0.08. To improve event location, ODNR-DOGRM deployed a seismic array with 4 short-period stations in late Oct. Using HypoDD on the array data, a cluster of 30 seismic events that occur between Nov 2 and Dec 13, 2013 were located below the 3 wells and defined a vertical plane striking N92. A composite focal mechanism using 5 of the best-located events resolved an East-West trending vertical focal plane (striking N97), matching the earthquake distribution. Thus, based on temporal and spatial occurrence of the above microseismicity, the concurrent hydraulic fracture operation above it most probably activated a preexisting fault in the area.

Triggered Earthquakes Far From the Wellbore: Fluid Pressure Migration and the 2008–2014 Jones Swarm, Central Oklahoma

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Earthquake relocations and hydrogeologic modeling show that the Jones earthquake swarm, occurring near Oklahoma City since 2008, is linked to disposal wells injecting high volumes of water along the Nemaha Fault. Felt and recorded earthquakes in the Jones swarm began in 2008, approximately 15 km from four high-volume wastewater disposal wells. These wells dispose of ∼2–3 million barrels per month (4–5 million barrels per month cumulatively) in two adjacent locations on the downthrown side of the Nemaha fault. Earthquakes are observed to migrate away from these high-volume disposal wells up the structural dip and down hydraulic gradient. Hydrogeologic modeling shows that the increase in subsurface pore pressure resulting from the fluid injection is of sufficient magnitude to trigger slip on pre-existing faults. The region of increased pore pressure grows outward through time with injection. The larger, mapped faults in the subsurface may act as conduits or guides to fluid flow, and may transmit fluid pressure into basement. Our results demonstrate that wastewater disposal can raise fluid pressure and trigger earthquakes at tens of kilometers from the wellbore on existing faults.

Potential Case of Induced Seismicity from a Water Disposal Well in South-Central Oklahoma

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On September 17, 2013, a swarm of earthquakes began in Love County, Oklahoma, north of Marietta. These earthquakes began occurring about two weeks after injection began at a nearby disposal well. The largest earthquake was a magnitude 3.4, which did minor damage to structures in the epicentral area and had a maximum Modified Mercalli Intensity of VII. Local residents consistently feel magnitude 1.8 earthquakes. The earthquakes are occurring at shallow depths consistent with injection depths of the nearby disposal well. The sequence included 22 earthquakes of magnitude 2.0 or greater with more than 100 earthquakes identified during the period which injection occurred. Regional seismic stations provide poor coverage of the earthquakes, in part due to the shallow focal depths. A temporary network of six seismic stations was deployed in the area. This network greatly enhanced earthquake locations and dramatically improved the magnitude of completeness. Earthquakes continued after injection ceased but at a lower frequency and smaller magnitudes with only one felt earthquake. This area has seen similar shallow earthquake swarms in the past. It is important to address whether or not this swarm of earthquakes is caused by fluid injection at the nearby disposal or simply an unlikely coincidence. Techniques used to improve event identification and locations of the earthquakes

are presented. A statistical method to quantitatively address seismicity changes is adopted and implemented in a monitoring system, in the event injection resumes in the disposal well or in a nearby well that was recently completed. The operator of the disposal well is currently restricted on injection rates and volumes and has ceased operations, if injection resumes the results of the statistical monitoring and traffic light system will be presented.

Constraints on Recent Earthquake Source Parameters, Fault Geometry and Aftershock Characteristics in Oklahoma

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Since late 2009 a dramatic increase in seismicity has occurred in Oklahoma. The largest of these earthquakes was a series of three moderate, but damaging, events (Mw 4.8, 5.6, 4.8) that occurred over a span of four days in November 2011 near the towns of Sparks and Prague in central Oklahoma. Initial reports suggest that these earthquakes were induced by reactivation of the Wilzetta fault due to the disposal of waste water from hydraulic fracturing ('fracking'), a process used to extract oil and gas from established producing wells. The Wilzetta fault is a northeast trending vertical strike-slip fault that is well known structural trap for the production of oil and gas. Since the November 2011 sequence, hundreds of moderate-sized (M2-M3) earthquakes have occurred throughout Oklahoma, located near the town of Jones in north-central Oklahoma. The relationship among the recent earthquakes, waste water injection, and older structures is still not well understood.

Given the infrequent occurrence of damaging earthquakes in the central U.S., characterizing the recent Oklahoma earthquakes offers a rare opportunity to improve our understanding of earthquake hazard in this populous region as well as the relationship to waste water injection. We report on the earthquake sequence that began in November 2011 and on related aftershock sequences and subsequent events in the region. Modeling from this study allows us to constrain the detailed geometry of the reactivated Wilzetta fault, as well as source parameters (focal mechanisms, stress drop, rupture length) for the larger earthquakes. Preliminary results from the November 2011 Prague sequence suggest that subsurface rupture lengths of the largest earthquakes are anomalously long with very low stress drop. We also observe very high Q ($\sim$1000 at 1 Hz) that explains the large felt areas and we find relatively low b-value and a rapid decay of aftershocks.

The 2013 Seismic Sequence Close to the Gas Injection Platform of the Castor Project, Offshore Spain

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A spatially localized seismic sequence has originated few tens of kilometres offshore the Mediterranean coast of Spain, starting on September 5, 2013, and lasting at least until October 2013. The sequence culminated in a maximal moment magnitude Mw 4.3 earthquake, on October 1, 2013. The epicentral region is located near the offshore platform of the Castor project, where gas is conducted through a pipeline from mainland and where it was recently injected in a depleted oil reservoir, at about 2 km depth. We analyse the temporal evolution of the seismic sequence and use full waveform techniques to derive absolute and relative locations, estimate depths and focal mechanisms for the largest events in the sequence (with magnitude mbLg larger than 3), and compare them to a previous event (April 8, 2012, mbLg 3.3) taking place in the same region prior to the gas injection. Moment tensor inversion results show that the overall seismicity in this sequence is characterized by oblique mechanisms with a normal fault component, with a 30° low-dip angle plane oriented NNE-SSW and a sub- vertical plane oriented NW-SE. The combined analysis of hypocentral location and focal mechanisms could indicate that the seismic sequence corresponds to rupture processes along sub- horizontal shallow surfaces, which could have been triggered by the gas injection in the reservoir. An alternative scenario includes the iterated triggering of a system of steep faults oriented NW-SE, which were identified by prior marine seismics investigations. The most relevant seismogenic feature in the area is the Fosa de Amposta fault system, which includes different strands mapped at different distances to the coast, with a general NE-SW orientation, roughly parallel to the coastline. No significant known historical seismicity has involved this fault system in the past. Both of our scenarios exclude its activation, as its known orientation is inconsistent with the focal mechanism results.

Seismic Response to Power Production at the Coso and Salton Sea Geothermal Fields, South-Eastern CA: Using Operational Parameters and Relocated Events to Study Anthropogenic Seismicity Rates and Reservoir Scale Tectonic Structure

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With increasing demand for geothermal power, it is important to understand how geothermal operations interact with local (and regional) seismicity, and to determine if seismicity rates are predictable from operational parameters. Furthermore, geothermal injection and production strategies can be improved by identifying, locating and characterizing related earthquakes within the tectonic related background seismicity. We focus specifically on the Coso and Salton Sea geothermal fields in California. Local seismicity is statistically declustered into background and aftershock rates, and we demonstrate that the background rate (at both fields) can be approximated during many time intervals at the 90% + confidence level by a linear combination of injection volume and the net extracted volume. We also use relative relocations and focal mechanisms from Yang et al. (2012) to map fault planes within the Coso geothermal field. We use Bayesian S-wave picking of Coso borehole network microearthquake data and fully-nonlinear 3D hypocenter grid searches to obtain 18000+ well located hypocenters in the geothermal field. Coso geothermal seismicity is not diffuse; 87% of the hypocenters occur within 25 m of planes consistent with tectonic processes along the eastern California shear zone. 83% associate with vertical and steeply-dipping conjugate N-NW dextral and NE sinistral strike slip planes, 12% with on normal-slip planes with dips of 35–70 degrees, and 5% with reverse-oblique-slip on steeply-dipping planes. The non-diffuse nature of seismicity suggests that induced events occur preferentially on pre-existing structures and that flow is concentrated in fractures. With minimum horizontal stress oriented at 81 degrees, and no normal faults, in the western part of the field, and 106 degrees and pervasive normal faults in the eastern portion of the field, structures that are favorably oriented in the current stress field appear to be most commonly activated by geothermal operations.

Induced Seismicity Mechanisms at The Geysers Geothermal Field from the Analysis of Stress Field Variations Related to Fluid Injection

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We investigated spatial, kinematical and magnitude characteristics of induced seismic events occurring during different fluid-injection stages to determine the potentially predominant mechanism of induced seismicity. We analyzed a relocated hypocenter catalog from a particular seismicity cluster in the northwest The Geysers geothermal field. Here, significant temporal variations of the stress field orientation related to peak-flow rates of fluid injected were detected. This observation has been further interpreted as an effect of increase in pore pressure and horizontal stress magnitudes at reservoir depth. Short-term temporal increases in the relative stress magnitude during peak-injection support this interpretation.

The improved resolution within the relocated seismic event cloud allows identifying several spatio-temporal features. We find that seismic events during peak-injections occur at greater distances from the injection point towards the north-east, i.e. parallel to the maximum horizontal stress. In contrast, during lower injection rates the seismicity migrates dominantly to the south.

Most of the events present normal faulting kinematics. However, during peak-injections the number of thrust and/or strike-slip events increases suggesting the increase in stress state at the reservoir. These events occur further away from the well than the normal-faulting events. Also, during peak-injection times, the cumulative seismic moment released by thrust/strike slip events is increasing compared to that of normal faulting events. The b values during peak injection periods also decrease.

Our results suggest that prior to peak-injection periods, the seismicity of the cluster is connected with the thermal fracturing of the reservoir rock. However, during peak injections, the limited pore pressure increase may play a significant role,

even though pore pressure remains relatively low since the water is not pumped under high pressure but free falls down the borehole.

Geomechanical Reservoir Characterization Using Induced Seismicity and State-of-The-Art Waveform Processing Techniques

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In this study we present the application of three waveform processing techniques to investigate physical processes in reservoirs related to fluid injection operations performed at Berlin and The Geysers geothermal fields. An initial hypocenter catalog of 581 fluid-induced seismic events recorded at the Berlin geothermal field was significantly revised and refined using double-difference relocation and spectral ratio methods. The average resolution within the seismic cloud was improved by a factor of 15. The application of the spectral ratio technique effectively cancelled path effects resulting in improved source parameters for the seismic events. The refined catalog allowed for a detailed analysis of spatio-temporal evolution of the seismicity related to fluid injection initially not visible due to limited resolution: We find a clear clustering of events around the injection intervals and in areas of high conductivity, observe a migration of the seismicity away from the injection interval with increasing injection rates and along pre-existing faults, detect larger seismic events in undamaged parts of the faults and in areas with a high conductivity gradient. We also find that the static stress drop of seismic events is decreasing with distance from the injection point. The stress inversion technique was applied to a seismicity cluster in the NW part of The Geysers geothermal field in California in order to demonstrate how this technique can contribute to the monitoring of reservoir-geomechanical processes occurring in response to short-term fluid-injection. The analyzed cluster composed of 742 events with fault plane solutions was used to look for time-dependent stress changes. We observed significant rotations of the stress field orientation directly related to increasing flow rates during peak-fluid injection. Moreover, these stress rotations are reversible documenting that stress field orientation might serve as an additional parameter for reservoir monitoring.

Moment Tensor Dynamics of Hydraulic Fracturing in Hydrocarbon Reservoirs

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Hydraulic fracturing of shale and tight sand reservoirs is employed to stimulate hydrocarbon reservoirs by pumping fluid and particulate matter through the targeted formations, either by creating new fractures or stimulating the pre-existing natural fracture network. This process is normally seismogenic, generating microseismicity (usually < M0) that is either responding to the pore pressure perturbations as a shear-tensile failure, to the Coulomb stress perturbation of the injection, or some combination of these two end-members. Microseismic monitoring, though borehole-deployed tool strings of omni-directional geophones, allows for delineation of the associated seismicity, revealing the zone of influence of the fracturing and with a number of assumptions, the volume of hydrocarbon that can be recovered after stimulation. In order to reduce the number of assumptions necessary to translate the seismicity into a measure of stimulated volume, the mechanisms of the microseismicity can be determined in cases where the waveforms are observed from a sufficient angular distribution. With downhole instrumentation, this condition translates to high-quality waveforms being observed from arrays deployed in multiple wellbores around the injection. The pattern of mechanisms associated with these hydraulic fractures begins to reveal the underlying dynamics: as fluid is pumped into formation, events grow out from the treatment zone; the addition of proppant can trigger a change in the dynamics and generate 'breakout' events that are initially relatively isolated away from the cloud of seismicity around the treatment well, occurring hundreds of meters away and dominated by shear or shear-tensile mechanisms; as the treatment continues, events backfill the gap between the breakout and initial seismicity, with opening dominant mechanisms. We will illustrate this behaviour through case studies in shale and tight sandstone formations.

Seismic Hazard and Ground Motion Implications of Induced Seismicity

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Induced seismicity poses a significant and as-yet-unquantified risk to the integrity of critical structures, such as major dams, as new unconventional energy activities (including hydraulic fracture treatments and wastewater disposal) are currently being planned and/or conducted in close proximity (within 10 km). The addition of a new seismicity source, such as a disposal well, fundamentally alters the seismic hazard at nearby sites. The additional hazard from the induced seismicity source may overwhelm the natural hazard, particularly at the low-probability levels of interest to critical structures. The impact is greatest in regions of low-to-moderate seismicity, for which existing facilities were designed with the implicit understanding that expected ground motions are modest. The impact is further exacerbated by the shallow depth of the induced events, which may result in large ground-motion amplitudes being generated from moderate events at very close distances.

This presentation overviews the ground-motion and hazard issues associated with the addition of an induced seismicity source in close proximity to a site, in a low-seismicity region. I show that IF an induced seismicity sequence is initiated, then its contribution to hazard will greatly exceed that from the pre-existing natural hazard. This arises due to the very close proximity of the source to the site, and the fact that the background hazard is low. Therefore, it is crucial to assess the likelihood and rate parameters of the potential induced seismicity sequence; this would allow us to multiply the hazard parameters for the induced-seismicity source by the appropriate conditional likelihood parameters, and obtain a reasonable estimate of the added hazard. Characterizing the hazard contributions of induced seismicity sequences, for operations that have not yet been initiated, is a complex problem that will provide a grand challenge in engineering seismology over the coming decade.

Quantifying the Seismic Hazard From Natural and Induced Earthquakes

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Induced earthquakes are believed to be at least partially responsible for the dramatic increase in seismicity in the Central and Eastern US over the past 12 years, yet they are presently excluded from USGS estimates of earthquake hazard. Here we propose an approach to include potentially induced earthquakes into the USGS National Seismic Hazard Map that deemphasizes the need to evaluate whether the seismicity is natural or man-made.

We first compile a list of areas of increased seismicity, including areas of known induced earthquakes. Using areas of increased seismicity (instead of just induced earthquakes) allows us to assess the hazard over a broader region, avoiding the often-difficult task of judging whether an earthquake sequence is induced.

We then estimate the earthquake hazard for each zone using a four-branch logic tree: (1) The increased seismicity rate represents short-term variation within a longer-term background seismicity rate. Thus, these earthquakes would be included in the background seismicity rate catalog. (2) The increased seismicity rate is a new and permanent addition to the background seismicity. Thus, the background seismicity rate is computed beginning at the time of the earthquake rate change (3) Induced earthquakes are responsible for the increased earthquake rate and they should be accounted for separately. This branch would compute different magnitude-frequency distributions for both kinds of events. The hazard from both would then be summed (4) The increased seismicity rate will decay back to the background seismicity rate. This could be applied to natural earthquake swarms or areas where industrial activity has stopped.

Based on the understanding of an individual earthquake sequence, one could weight these logic tree branches as appropriate. Although an imperfect solution, this approach is a first step in accounting for the contribution of both induced earthquakes and variations in natural earthquake rates to seismic hazard.

Managing Seismic Hazard Due to Induced Earthquakes in Central Arkansas through Partnership between Scientific and Regulatory Agencies

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Since the first fluid-waste disposal well associated with the Fayetteville Shale gas play became operational in April 2009, central Arkansas has experienced an increase in the rate of small and moderate earthquakes. Seismic activity in the area includes both naturally occurring and induced earthquakes that tend to happen in spatial

and temporal clusters. The Center for Earthquake Research and Information and the Arkansas Geological Survey closely monitor the area using 5 portable, real-time, broad-band stations (in addition to permanent and transportable array stations) to focus on specific sites of suspected induced seismicity. We communicate any concerns directly to the agency charged with regulating Underground Injection Control (UIC) wells in the state, the Arkansas Oil and Gas Commission (AOGC). The largest and most significant cluster of induced earthquakes in this area occurred between August 2010 and July 2011 where a previously unknown fault, the Guy-Greenbrier fault ($\sim$13km long), was illuminated by thousands of earthquakes ($M \leq 4.7$). Since a 13km long fault can potentially produce a M6 earthquake if it slips as a single event, we informed the AOGC that continued fluid injection at UIC wells in close proximity to the fault risked causing a potentially damaging earthquake. Four nearby UIC wells were shutdown and plugged. Earthquake activity on the fault dropped dramatically and soon essentially ceased, thus providing strong evidence that the earthquakes had indeed been induced. The fault remains seismically quiet after three years. The AOGC also established a moratorium area to exclude UIC wells in the area surrounding the fault. Induced earthquakes still occur in proximity to some UIC wells outside the moratorium area, but earthquake rates have been low and earthquake magnitudes have been less than 3.5. This provides a good example that human influence can both increase and decrease the induced earthquake hazard.

Protocol and Best Practices for Addressing Induced Seismicity Associated With Enhanced Geothermal Systems (EGS)

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To address public concern and gain acceptance from the general public and policymakers for the development of Enhanced Geothermal Systems (EGS), the U.S. Department of Energy (DOE) sponsored the development of a Protocol and Best Practices document to address induced seismicity. The purpose of the documents is to provide guidance to both industry and regulators on how to identify the important issues and necessary parameters for the evaluation, estimation, and mitigation of possible adverse effects associated with induced seismicity in EGS projects. The documents provide a set of general procedures and specific useful steps that geothermal project proponents can take to understand, quantify and manage the risk associated with induced seismicity. The procedures are not prescriptive, but instead recommend approaches to engage public officials, industry, regulators and the public at large, with the goal of facilitating the project approval process, avoiding delays and promoting safety. Seven basic steps are outlined in the Protocol and the Best Practices describes the approaches used in those steps in detail. They are: 1) perform preliminary screening evaluation; 2) implement an outreach and communication program; 3) review and select criteria for ground vibration and noise; 4) establish local seismic monitoring; 5) quantify the hazard from natural and induced seismic events; 6) characterize the risk of induced seismic events; and 7) develop a risk-based mitigation plan. The over-arching purpose of both documents is to provide a framework in which to evaluate, estimate and mitigate the risk associated with induced seismicity in EGS projects. Due in large part to the increased attention to induced seismicity caused by hydraulic fracturing and disposal of the resulting wastewater by injection, the Protocol and Best Practices are now being used by the oil and gas industry and its regulators to formulate strategies for mitigating the associated risks.

Large and Damaging Earthquakes of 2013/2014

Oral Session · Thursday · 8:30 AM · 1 May · Room 2 Session Chairs: Gavin Hayes, Thorne Lay, Harley Benz and Charles Ammon

From Simple to Complex: Source Properties of Some Recent Large Earthquakes Using Seismic and Geodetic Data

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We present results from studies of recent significant earthquakes, including the Santa Cruz Islands (Mw 8.0, Feb, 2013), Khash, Iran (Mw 7.7, Apr. 2013), and Awaran, Pakistan (Mw 7.7, Sep. 2013) events. We integrate moment tensor inversions, teleseismic fault modeling, geodetic observations, aftershock studies and regional tectonics to place these earthquakes into a broad seismotectonic framework.

We find that the Santa Cruz Islands earthquake generated a vigorous aftershock sequence, producing more than twice as many large strike slip aftershocks as previously observed in any megathrust sequence. Detailed finite fault analyses and stress transfer modeling also show this event likely triggered an episode of aseismic slip on the adjacent subduction zone interface over the two days following the mainshock.

For the Khash earthquake, we combine seismic and geodetic slip models. Together with waveform depth modeling, we show this event initiated at a depth of 80+ km and ruptured a vertical width of 50 km, half of the subducted oceanic lithosphere. We hypothesize that the Khash earthquake likely occurred as the combined result of dehydration embrittlement and slab bending stresses acting on a preexisting fault formed prior to subduction.

For the Awaran earthquake, we use analysis of optical imagery to define a 200+ km long rupture along an arcuate fault system. Combined with detailed surface rupture mapping from high-resolution optical imagery, and multi-strand finite fault inversions of geodetic and teleseismic data, these results reveal a relatively simple and continuous rupture, with slip occurring at shallow depths ($<$7–8 km) over the entire rupture length. Higher resolution imagery reveals small-scale complexity to the rupture, however, including regions of oblique-slip and distributed surface faulting. Together, these studies highlight the advances in understanding made possible by considering multiple independent observations of earthquake rupture.

Coulomb Stress Changes Resulting from the Mw 7.7 2012 Haida Gwaii Earthquake

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This study examines spatial changes to the local stress field resulting from the October 28, 2012, M_w 7.7 Haida Gwaii earthquake, which occurred west of Moresby Island off the coast of British Columbia. This event is thought to have occurred on a NE-dipping, blind thrust fault rather than on the sub-vertical Queen Charlotte Fault that represents the Pacific – North American plate boundary. This was the largest earthquake along the Canadian portion of this plate boundary since the 1949 M_s 8.1 Queen Charlotte earthquake.

The USGS software 'Coulomb' is used to quantitatively estimate the effect of the mainshock on the background stress field, the known aftershock nodal planes, and the nearby Queen Charlotte Fault. We use two different mainshock finite fault models, both of which are seismologically-derived (by Lay and Hayes, separately) and subsequently adapted by K. Wang to account for the motion detected at four nearby GPS stations. We also use the best-located set of aftershocks with information provided by a temporary array of ocean bottom seismometers. Preliminary results indicate an apparent clustering of aftershocks slightly seaward of the main thrust, which is consistent with the modeled zone of promoted normal failure likely related to extension in the footwall. Using existing models, we have found a high number of aftershocks to be consistent with triggering by the mainshock, suggesting that static stress is a dominant control in the months following a large earthquake in this area.

Additionally, we find loading, greater than the threshold for triggering, on the Queen Charlotte Fault in an area believed to be within a seismic gap. This work provides an improved understanding of the evolving seismic hazard along the Queen Charlotte margin, while simultaneously testing the usefulness of Coulomb modeling in this environment.

Investigating Dynamic Interactions Between the October 2012 Haida Gwaii and January 2013 Craig Earthquakes

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The M_w 7.8 (28 October 2012) Haida Gwaii earthquake and the M_w 7.5 (5 January 2013) Craig, Alaska earthquake occurred just 400 km and 68 days apart from each other. The short duration and distance between the events poses the question of whether these two events are related. We combine existing data from networks in Alaska and Canada, including a temporary network installed in the Haida Gwaii islands, to search for precursory activity prior to each

of the events. In order to improve the catalog completeness compared to the Alaska Earthquake Information Center (AEIC) and Canadian National Seismic Network (CNSN) catalogs, we utilize a 'matched'-filter technique to identify potential missing earthquakes before and after each mainshock. This technique utilizes existing cataloged waveforms as templates to identify new events in the continuous recordings. We examine the seismic activity prior to and following each event to determine whether any dynamic or delayed triggering of earthquakes or tremor occurs regionally due to these earthquakes. We have preliminary evidence that the Haida Gwaii earthquake directly triggered small earthquakes on the Fairweather Fault. In addition, triggered tectonic tremor from the Haida Gwaii and Craig events has already been identified on the Eastern Denali Fault (Zimmerman et al., submitted to EPSL). Finally, in response to the Haida Gwaii earthquake, a number of land and ocean-bottom seismometers were installed near the epicenter (James et al., 2013). As an assessment of the sensitivity of that earthquake rupture zone, we will assess whether the later-occurring Craig earthquake triggered any increase in aftershock activity within the Haida Gwaii region. The static and dynamic transmission of stresses from large earthquakes has important implications for transient fault zone loading in areas adjacent to mainshock rupture zones.

Magnitude 7.5 Earthquake of 5 January 2013 on Queen Charlotte Fault in Southeast Alaska

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A magnitude 7.5 earthquake occurred on January 5, 2013 in southeast Alaska. It ruptured ~150-km long segment of the Queen Charlotte fault, a strike-slip fault that marks the boundary between the Pacific plate to the southwest and the North American plate to the northeast. This earthquake was located within the northern end of the 1949 magnitude 8.1 rupture and south of the 1972 magnitude 7.6 event, i.e. it most likely filled a gap between the two earlier ruptures. A network of real-time seismic stations in southeast Alaska and an additional real-time station installed several days after the mainshock in Port Alexander recorded the aftershock sequence. Several continuous Plate Boundary Observatory (PBO) GPS stations in the southeast Alaska also recorded this event. In addition, a month-long deployment of a small network of Ocean Bottom Seismometers in June 2013 recorded aftershock activity. Due to the offshore location and sparse seismic network, reliable aftershock solutions with on-land seismic network are limited to magnitude 2.5 and greater. The Alaska Earthquake Center reported about 350 aftershocks through the end of 2013. The largest aftershock, magnitude 5.8, occurred one month after the mainshock. In total, 20 aftershocks with magnitudes 4 or greater were recorded. Aftershocks are not limited to the main fault strand and some are located up to 40 km away from the main fault rupture. This earthquake had super-shear rupture propagation along ~100 km to the north of hypocenter. Several inversion and modeling techniques were applied to seismic and geodetic data to investigate rupture velocity. Both theoretical and empirical Green's functions were used in inversion and modeling, which indicate a consistent super-shear rupture velocity of 5.5 to 6 km/s, higher than the crustal and upper-mantle S-wave velocity and approaching the P-wave velocity. Post-seismic deformation is continued to be monitored with regional geodetic network operated by the PBO.

Seismic Slip Distribution of Large Inter- and Intra- Plate Oceanic Strike-slip Earthquakes

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We determine the depth distribution of seismic rupture, fault orientation, and rupture velocity of recent, large oceanic strike-slip earthquakes using teleseismic body-waves. Oceanic strike-slip earthquakes can be used to examine how seismic rupture is accommodated along a relatively simple thermal and compositional fault structure. Seismic rupture in oceanic lithosphere is known to extend into the upper mantle, but current observations are insufficient to identify the control on depth of brittle failure and location of aseismic slip. By determining the slip distributions of the largest well-recorded oceanic strike-slip events, we will add further observations as evidence pointing to temperature, composition, or fault geometry as the primary mechanism regulating seismic rupture. The focus will be on two study areas: the Indian Ocean off the coast of Sumatra and the Scotia Sea around the South Sandwich Islands where two $M_W \geq 7$ earthquakes occurred in 2013. Sumatra represents intraplate deformation of 40 to 70 My oceanic lithosphere and South Sandwich Islands represents primarily interplate earthquakes on transforms offsetting lithosphere of 0 to 40 My. Deeper seismic slip is observed in the older lithosphere of Sumatra than the shallower slip observed in the younger lithosphere of South Sandwich Islands, consistent with temperature as the primary control on seismogenic width. Determining the orientation of the faults ruptured in Sumatra can help reconcile conflicting views of the existence of recent east-west faulting in the Indian Ocean. Fault orientation and extent in the South Sandwich Islands is needed to map the active faults and plate boundaries of the Scotia Sea, an inaccessible region with tectonic geometry predominantly determined from seismicity. Strike-slip events in other tectonic settings, such as the M_W 7.5 January 5, 2013, Southeastern Alaska earthquake, will be modeled to strengthen observations.

How the 2013 Lushan Earthquake (Ms=7.0) Triggered its Aftershocks: Insights from Static Coulomb Stress Change Calculations

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The Lushan earthquake (Ms=7.0) occurred at 08:02 Beijing Time (00:02 UTC) on April 20, 2013, located on the eastern margin of the Tibetan Plateau, where 2008 Ms8.0 Wenchuan earthquake took place. It is another strong quake following the Wenchuan earthquake occurred on the Longmen Shan thrust fault. A large number of aftershocks were recorded after the main shock. To investigate how the aftershocks are triggered, we firstly relocate the 6-month aftershock sequence by double-difference algorithm. Next, we calculate Coulomb failure stress changes imparted by the Lushan main shock both on the optimally oriented plane and on the nodal planes in focal mechanisms of the large aftershocks. Then we examine the correspondence between the Coulomb failure stress changes and the spatial distribution of the aftershocks. The computed results show that most of the aftershock hypocenters did not occur on the region with the positive Coulomb stress changes imparted by the Lushan earthquake. This implies the coseismic static Coulomb stress changes may not be the governing process for aftershock genesis. In contrast, postseismic stress transfer by the processes of afterslip and pore fluid flow may play an important role in aftershock triggering based upon the spatiotemporal distribution of the aftershocks.

Rupture History of the 2013 Mw6.8 Lushan, China Earthquake Based on Strong Motion Data Inversion: A High-Angle Blind Thrusting Event

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The Mw 6.8 Lushan earthquake occurred on April 20 in Sichuan province, China, and resulted in up to 200 fatalities and tens of thousands injuries. This latest earthquake occurred at the southwestern part of the Longmenshan fault zone (LMSF), which also hosted the 2008 great Wenchuan earthquake to the northeast. Field investigation immediately after the Lushan earthquake found no obvious evidence of surface breaks, but documented surface cracks indicating that the Lushan earthquake occurred on a blind thrust fault (Li et al., 2013; Xu et al., 2013). Focal mechanisms determined for the Lushan earthquake also indicated that the coseismic slip was thrust, but several contained non-double-couple components which may possibly indicate a variation is fault geometry or coseismic slip rake. Aftershocks indicate that the main fault surface was along trend of the general strike of the LMSF, and dipping to the northwest, similar to the 2008 Wenchuan earthquake; however, there are also aftershocks that delineate a southeast dipping plane to the northeast of the main thrust fault. We use local strong motion data to infer the rupture history during the Lushan earthquake, including constraining the dip of the fault surfaces. We find that the majority of the coseismic slip occurred on a steeply dipping thrust ramp, with minor amounts of slip on a steeper dipping fault closer to the surface. There is additionally some suggestion of coseismic slip on a mid-crustal sub-horizontal decollement, although the earthquake did not initiate on the decollement. If the adjacent southeast dipping fault is included in the coseismic slip solution, the strong motion data require a minor amount of normal-sense coseismic slip on that structure. This normal slip is delayed from the initiation of the main thrust slip, and the early thrust slip produced positive Coulomb stress changes on this adjacent normal fault.

Rupture Process of the November 17, 2013 M_w 7.8 Scotia Sea Earthquake

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On November 17, 2013, a very large (Mw 7.8) strike-slip earthquake occurred on the South Scotia Ridge (SSR), the boundary between the Scotia and Antarctica plates. The epicenter (60.27°S, 46.40°W) is northwest of the South Orkney micro-continent. The SSR is the most seismically active portion of the entire Antarctica plate boundary, having experienced about 10 M 7+ events since 1908 with additional events just east of the South Sandwich Island subduction zone. The earthquake sequence initiated with Mw 6.1 (Nov. 13) and 6.8 (Nov. 16) events located ~50 km west of the mainshock, and aftershocks extend ~250 km eastward along the SSR. On Nov. 24, 2013, a potentially triggered left-lateral Mw 7.0 event occurred ~900 km northwest on the North Scotia Ridge, the northern boundary of the Scotia plate with South America. The mainshock W-phase and GCMT point source inversions of long-period seismic waves indicate left-lateral strike-slip displacement on a fault striking 97°–102° and dipping southward at 45°–50°, with seismic moment of ~5.2–5.5 × 10^{20} N-m. Eastward rupture expansion for over 250 km at ~2.5 km/s is inferred from back-projections of teleseismic short-period P waves for networks of stations in the Americas and Australia, and from directivity in the effective source time functions for global long-period surface waves. Two intervals of large moment rate occurred from 20–50 s and 70–90 s after the origin, based on finite-fault inversion of broadband teleseismic P and SH waves. Iterative modeling of a 1 Hz GPS ground motion recording at station BORC on Laurie Island (South Orkney Islands) is used to constrain the source rupture parameters. The rupture extends to the vicinity of the rupture zone of an August 4, 2003 Mw 7.6 earthquake, which appears to have a similar southward dipping left lateral strike slip geometry. The 2013 event has relatively high short-period seismic wave energy release and high moment scaled radiated energy (ER/M0 ~3 × 10^{-5})

The Implosive Component of the 2013 Okhotsk Sea Deep Earthquake: Evidence from Radial Modes and Constraints from Geodetic Data

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Ever since Bridgman's [1945] original suggestion, the presence of an implosive component in the source of deep earthquakes has long been a passionately debated subject, which is re-opened by the occurrence of the 2013 Sea of Okhotsk earthquake, the largest ever recorded deep event. The analysis of the fundamental and first overtone radial modes, 0s0 and 1s0, allows the resolution of such a component without trade-off with the relevant deviatoric component. We document the presence of an implosive component valued at 2% of the scalar moment tensor (but 9% of the deviatoric component exciting radial modes). The implosive component is also resolved by CMT inversion when the zero-trace constraint is relaxed, but with a significantly larger amplitude (8% of the scalar moment) [M. Nettles, pers. comm., 2013].

The near field of three-dimensional static deformation by the earthquake is reconstructed from data at permanent GPS stations in the epicentral area, with maximum observed deformations on the order of 1 cm (horizontal) to 2 cm (vertical). Preliminary modeling indicates that the influence of the proposed implosive component (especially as derived from CMT inversion) may be resolvable from this dataset at critically located GPS stations, of which a full investigation will be presented.

Slip Models for the 2013 M7.7 and M6.8 Balochistan Earthquakes in Pakistan

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A large Mw 7.7 earthquake struck a remote area in the Balochistan region of western Pakistan on 24 September 2013. The nearest city of Awaran was heavily damaged along with many smaller towns and villages. We use both geodetic measurements from satellites (optical and radar) and teleseismic waveforms to resolve the slip of the Mw 7.7 mainshock and a large Mw 6.8 aftershock that struck on 28 September. The optical Landsat 8 satellite, a joint project of NASA and USGS, imaged the entire length of the Mw 7.7 earthquake rupture on 10 and 26 September, and fortunately both 185 km-wide scenes were cloud-free. We used the Caltech COSI-Corr package to do sub-pixel correlation and extract the horizontal components of surface displacements. The German TerraSAR-X synthetic aperture radar (SAR) satellite imaged two parts of the fault on 27 September using two different narrow stripmap beams. The Canadian Radarsat-2 satellite imaged the western part of the area. We ran both pixel offset tracking (essentially the same as sub-pixel correlation) and regular SAR interferometry (InSAR) to measure the displacements in the cross-track and along-track directions from the TerraSAR-X and Radarsat-2 data for the mainshock. The German TerraSAR-X SAR also imaged the eastern part of the area on 25 October with a wide-swath ScanSAR image. We also ran a type of pixel offset tracking and InSAR analysis to measure two components of the displacements for the mainshock and aftershock. We ran joint inversions of the geodetic data and teleseismic waveforms to estimate the slip for the mainshock with its roughly 200 km rupture length and the M6.8 aftershock with its rupture length around 50 km. The aftershock rupture overlaps with the northeast end of the mainshock rupture, but occurred in an area where the mainshock slip was much smaller than the western 2/3 of the main rupture.

Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)

Oral Session · Thursday · 1:30 PM · 1 May · Room 2 Session
Chairs: Jim Mori, David Wald, and Emily C. Roland

Low Coseismic Friction on the Tohoku Fault Determined from Temperature Measurements

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The amount of frictional resistance on a fault during an earthquake is an outstanding unknown of earthquake physics. Heat around the fault after an earthquake can provide insight, as it records the integrated energy dissipated by friction. In July 2012, the JFAST project (IODP Expedition 343/343T) installed a temperature observatory across the fault that generated the March 2011 Mw9.0 Tohoku earthquake where slip was ~50 m near the trench. After 9 months, the complete sensor string was recovered, implying there was negligible afterslip at this location during the deployment. The data reveal a 0.31°C temperature anomaly at the plate boundary fault requiring 28 MJ/m^2 of dissipated earthquake energy. The corresponding effective friction coefficient of 0.08 is considerably smaller than static values for most rocks (0.6) and compatible with high-velocity friction experiments on the fault core material. The corresponding coseismic frictional stress of ~0.6 MPa suggests nearly complete stress drop locally.

Stress State near Updip End of the 2011 Tohoku-Oki Earthquake Inferred from OBS Aftershock Observations

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The 2011 Tohoku-Oki earthquake (Mw 9.0) ruptured a roughly 200 km wide and 500 km long segment of the subduction fault along the Japan Trench (e.g., Yagi and Fukahata, 2011). The most significant feature of the 2011 Tohoku-Oki earthquake is a huge coseismic slip (> 50 m) near the trench axis. After the 2011 Tohoku-Oki earthquake, shallow normal-faulting seismicity has been active in the incoming/subducting Pacific plate near the Japan Trench (e.g., Asano

et al., 2011). Furthermore, a pair of large Mw 7.2 intraplate earthquakes, a deep reverse-faulting event followed by a shallow normal-faulting event, occurred near the trench axis on December 2012. According to the Global CMT project (GCMT, http://www.globalcmt.org/), centroid depths of these events are 57.8 km and 19.5 km. These earthquakes near the updip end of the 2011 rupture area reflect stress state related to the large near-trench slip during the 2011 earthquake. To investigate the stress state near the trench axis, we have conducted a series of ocean bottom seismograph (OBS) observations near the trench axis since the occurrence of the 2011 Tohoku-Oki earthquake. These observations provided accurate hypocenter locations and focal mechanisms in both seaward and landward of the trench axis. The earthquakes observed by the OBSs were located mainly within the overriding and incoming/subducting plates, but very few on the plate interface. Most of the focal mechanisms indicate normal or strike-slip faulting with T-axis normal to the trench axis. This indicates that tensional stress is dominant in the trench axis area. The trench-normal extensional earthquakes were shallower than about 35 to 40 km. On the other hand, most seaward part of the seismicity within the overriding plate is characterized by a cluster of trench-normal compressional earthquakes, which may relate to spatial variation of the frictional behavior of the shallowest part of the megathrust.

Large Shallow Slip of the 2011 Tohoku-oki Earthquake

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The 2011 Tohoku-oki earthquake (Mw9.0) produced a huge amount of slip (40 to 60 meters) on the shallow portion of the subduction zone close to the Japan trench. Such large fault displacement was unexpected for the region and was mainly responsible for the tsunami that devastated much of the northeast coast of Honshu. Using results from the Japan Trench Fast Drilling Project (JFAST) which sampled the fault in the region of large slip and estimated the fault friction level from temperature measurements, we can begin to understand the conditions for the very large fault slip. The plate boundary fault zone is localized in a thin layer (less than 5 meters) of highly deformed pelagic sediments. From the temperature measurements and laboratory experiments, these fault zone rocks are shown to have very low dynamic frictional properties. This implies that once slip initiates, the friction drops to a very low value which is conducive to large slip and a complete release of the accumulated shear stress.

Similar to the 2011 earthquake, the 1896 tsunami earthquake in a nearby region is also thought to have had large slip on the shallow portion of the subduction zone close to the Japan trench. The thin fault zone of low friction pelagic clay may control this behavior for both earthquakes. However, not all great earthquakes along the Japan Trench have large fault displacements to the trench. The 1968 (Mw8.3) and 2003 (Mw8.3) Tokachi earthquakes were more typical subduction zone earthquakes and probably did not rupture out to the trench. We will discuss some of the factors related to earthquakes that rupture close to the trench.

Constraining the Broadband Slip History of 2011 Tohoku Earthquakes Using a Two-Step Finite Fault Approach

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A two-step finite fault inversion approach is developed to improve our understanding to the distributions of high frequency seismic radiation during large earthquakes and their relationship with the corresponding fault slip distribution. It uses the nonlinear finite fault inversion method to constrain the general slip pattern of rupture process and then further improve the fits to high frequency by subsequently Landweber iterations with nonlinear causality and moment constraints. This new approach naturally considers the near-source reverberation of seismic waves and fault geometry, which are significant but were generally ignored during conventional back-projection analyses. We have applied this method to the 2011 Mw 9.1 Tohoku earthquake using teleseismic P wave data. Our results reveal two zones of fault patches with apparent higher high-frequency (1–2 Hz) seismic radiation during this giant earthquake. One zone is associated with the downdip edge of the co-seismic rupture, consistent with previous back-projection studies (e.g., Koper et al., 2011; Wang and Mori, 2011 and Meng et al., 2011). Another zone locates at the up-dip direction of the hypocenter, roughly marking the down-dip edge of the near-trench fault patch with over 60 m peak slip. The fault patches with higher far field high-frequency radiation are also the regions where the slowdowns of rupture propagation in their vicinities were found during our nonlinear finite fault inversion. The correlation between apparent high frequency seismic radiation and rupture kinematic rupture process inferred from broadband finite fault inversion are consistent with the classic dynamic mechanisms, i.e., suddenly decelerating of the rupture propagations near the edges of barriers and breaking into the stress singularity zones at the edges of the high slip patches (e.g., Madariaga, 1983).

Constraining Shallow Slip and Tsunami Excitation in Megathrust Ruptures using Seismic, Ocean Acoustic, and Tsunami Waves Recorded on Ocean-Bottom Sensor Networks

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Networks of seismometers and pressure gauges deployed offshore in subduction zones hold much promise for illuminating the megathrust rupture process and improving local tsunami warning systems. We aim to characterize the offshore wavefield generated by great megathrust events, with the specific objective of identifying signatures of shallow slip. Here we present dynamic rupture simulations from the 2011 Mw 9.0 Tohoku event. Shallow slip near the trench is influenced by frictional properties beneath the frontal prism. Even when velocity-strengthening behavior extends several tens of kilometers landward from the trench, the rupture reaches the trench with $\sim$30 m slip there. Our simulations, which include a compressible ocean, reveal pronounced wave excitation when the rupture reaches the seafloor. The largest waves are 14-s oceanic Rayleigh waves propagating offshore at a group velocity slightly less than the sound speed and carrying pressure changes in the water column $>$1 MPa. Their amplitudes are determined by the overall moment release of the earthquake, with little sensitivity to the shallow rupture process. The dominant wave signal in the landward direction is carried by leaking P-wave modes (or PL waves). These waves propagate toward shore at 6 km/s and are comprised, in part, of multiply reflected ocean sound waves carrying acoustic pressure changes of 0.1–1 MPa. Most remarkable is the sensitivity of oceanic PL waves to the shallow rupture process and tsunami excitation near the trench, with potential implications for local tsunami early warning systems. An obvious next step is to develop correlations between PL-wave amplitudes and tsunami wave heights. With this objective, we have extended our code by adding gravitational restoring forces, thereby enabling us to simultaneously model surface gravity waves (tsunamis) in the ocean along with seismic and acoustic waves and rupture dynamics.

Complete Stress Drop in Shallow Great Earthquakes

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Recent great earthquakes with significant shallow slip, including the 2011 M9.0 Tohoku, 2010 M8.8 Maule, and 2004 M9.2 Sumatra earthquakes, produce coseismic and postseismic rotations of the principal stress axes that imply complete or near-complete stress drop (Hasegawa et al., EPS, 2011; Hardebeck, GRL, 2012). A systematic analysis of coseismic stress rotations due to recent $M \geq 8$ subduction earthquakes shows little stress rotation below 25 km depth. This implies that the conditions that allow near-complete stress drop are limited to shallower depths, likely related to lower overburden pressure or to material properties in the near-trench region.

I first invert together all moment tensors of inter- and upper-plate events for stress orientation. Prior to each shallow mainshock, the maximum compressive stress axis is near horizontal, while immediately after the mainshock, both the maximum and minimum compressive stress axes plunge at $\sim 45°$. Dipping faults can be oriented for either reverse or normal faulting in this post-mainshock stress field, depending on dip, explaining the normal-faulting aftershocks observed after some mainshocks. The stress axes rotate back rapidly in the months following the Tohoku and Maule mainshocks, and in the southern part of the Sumatra rupture. A rapid postseismic rotation is possible because the near-complete stress drop leaves very little stress at the beginning of the postseismic reloading.

The spatial distribution of stress orientations before and after each mainshock is then mapped on a finer length scale to relate the complete stress drop regime to overburden pressure, material properties, and/or other fault behaviors. I bin events in the Tohoku, Maule, and Sumatra regions by both space and time, and invert their moment tensors. I will present preliminary results of the finer-scale spatial-temporal stress evolution, and relate the distribution of near-complete stress drop to depth and other observables.

Seismic Versus Aseismic Slip: Probing Mechanical Properties of the Northeast Japan Subduction Zone

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Fault slip may involve slow aseismic creep and fast seismic rupture, radiating seismic waves manifested as earthquake. These two complementary behaviors accommodate the long-term plate convergence rate of major subduction zones and are attributed to the fault frictional properties. It is conventionally assumed that zones capable of seismic rupture on the subduction megathrust are confined to within about 10 to 50km depth; however, the actual spatiotemporal extent of fault mechanical parameters remains elusive for most subduction zones. The 2011 Tohoku Mw9.0 earthquake, challenging this conventional assumption, provides a unique opportunity to probe the mechanical properties of the Japan subduction zone. Drawing on the inferred distribution of coseismic and postseismic slip, it has recently been suggested that portions of the megathrust are capable of switching between seismic and aseismic behavior. Investigating the coseismic and 15-month postseismic deformation of this event, we find that the coseismic rupture triggered widespread frictional afterslip with equivalent moment magnitude of 8.41, in addition to viscoelastic relaxation in the underlying mantle. The identified linear relation between afterslip and the cumulative number of aftershocks at 35–55 km depth suggests that most aftershocks are a direct result of afterslip. Using a rate-state friction model we constrain the heterogeneous fault mechanical parameters of the subduction thrust. Our results indicate a variable pattern along dip and strike and that velocity-weakening properties persist in the shallow part of the megathrust. This finding indicates that earthquakes with the size of the Tohoku earthquake will likely repeat in the future, highlighting the importance of characterizing the spatiotemporal extent of the fault mechanical properties elsewhere.

CMT Re-analysis of the Great 1964 Alaska Earthquake

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The very small number of instrumentally recorded $M > 9$ earthquakes makes each such event of particular scientific value. The recent $M \sim 9$ Sumatra-Andaman and Tohoku subduction-zone earthquakes were recorded on modern very-broadband seismometers with high dynamic range and have been studied in detail using modern seismological methods. Our knowledge of the source characteritistics of the $M \sim 9$ 1964 Alaska earthquake is much more limited. This event was recorded by seismographs of limited dynamic range, with the result that direct P-wave arrivals were off scale even at teleseismic distances, and surface-wave arrivals were off scale worldwide for hours following both events. No analysis of the long-period source characteristics of the 1964 Alaska earthquake has been conducted using modern moment-tensor inversion methods or techniques of seismogram synthesis. Here, we apply a modified centroid-moment-tensor analysis technique to the hand-digitized records of the 1964 Alaska earthquake originally collected by Dziewonski and Gilbert (1972). The data are of high quality, and the station coverage is good, though the portion of the data analyzed must be restricted to the G4-8 and R4-8 orbits of the Love and Rayleigh waves in most cases. Preliminary results are broadly consistent with those of Kanamori (1970), and suggest that the 1964 earthquake was larger than both the Sumatra and Tohoku earthquakes. We explore a range of parameter space, including for fault dip, and assess our results in comparison with available imaging results and recent seismic and geodetic studies of the geometry of the rupture region.

Recent Advances in Ground Motions Simulation Methods and Their Validation

Oral Session · Thursday · 8:30 AM · 1 May · Room 3 Session
Chairs: Christine Goulet and Kim B. Olsen

Three-Dimensional Ground-Motion Simulations of Earthquakes in the Hanford, Washington Area

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Observations and 3D finite-difference simulations for the Hanford area of eastern Washington state show that basin-edge generated surface waves at frequencies up to 2 Hz amplify and prolong the ground shaking compared to that expected from flat-layered velocity models. The Hanford site is a former nuclear production complex with large amounts of stored radioactive waste. The 3D model consists of a sedimentary basin with a relatively thin (130 m or less) layer of sediments above a thick sequence of basalts that overlie pre-Miocene sediments and basement. Recordings in the basin of a M3.7 earthquake at 20 km depth south of the basin show a prominent set of dispersed arrivals at 1–2 Hz following the S-wave. Synthetics derived from the 3D model match the observed later arrivals, whereas synthetics from flat-layered velocity models do not contain these arrivals. The simulations show that these later arrivals were high-frequency surface waves propagating in the sediments above the basalt, created by conversion of incident S-waves at the southern edge of the basin. 3D and 1D simulations were done for M6.7–6.8 earthquakes on the Rattlesnake Hills fault along the southern edge of the basin and M6.6 earthquakes on the Gable Mountain fault beneath the basin. The synthetics from the 3D model at some sites have spectral accelerations (SA) at 1–2 Hz that are 2 to 4 times higher than those from the 1D model, for earthquakes along the southern edge of the basin. This amplification is due to basin-edge generated surface waves. The 1–2 Hz SA of the synthetics from the 3D model for ruptures near the southern edge of the basin are significantly larger than those predicted from the NGA West 2 ground-motion prediction equations. We estimated the effects of the sedimentary basin on regional S-waves from earthquakes on the Cascadia subduction zone by using a dipping plane-wave source. The simulation for the 3D model produced SA values substantially larger than the flat-layered model.

Verification of Synthetic Near-Source Ground Motion Against Empirical GMPE and Physics-Based Stochastic Source Characterization for Future Earthquakes

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For the purposes of site-specific evaluation of ground motions for future earthquakes, there is an increasing awareness to use synthetic ground motion time series in combination with observed ground motion (if available) rather than solely empirical data usually interpolated and/or extrapolated from different sources and locations, particularly near the source where recorded data are sparse and ground motions are dominated by the source effects. Physics-based dynamic rupture modeling appears to be the best suitable approach to produce synthetic ground motions since it has the potential for identifying source-dominated ground motion phenomena and their variability. It requires the consideration of a large number of earthquake scenarios in a wide magnitude range, with the attempt to cover most of the potential future earthquakes and resulting ground motion variability. It also needs to be verified against empirical ground motion data from past earthquakes. In this study we show quantitatively the compatibility of a suite of synthetic data obtained from dynamic rupture models with empirical ground motion prediction equations (GMPEs) in terms of mean and standard deviation (sigma) of peak ground intensity measures. It is remarkable that our synthetic data are better comparable with the empirical GMPEs at distance larger than 10 km where empirical GMPE are robust, and the standard deviation from the synthetics are comparable to that of empirical GMPEs with little dependence on period and distance. We also propose to quantify the variability of finite source more systematically in physics-based source modeling because it controls the variability of simulated ground motions. The source variability characterized by stress drop and statistical correlations between kinematic source parameters contribute significantly to ground motion variability, providing useful insights to build stochastic source characterization for future earthquakes.

Summary of a Large Scale Validation Project Using the SCEC Broadband Strong Ground Motion Simulation Platform

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The goal of the SCEC Broadband Ground Motion Simulation Platform (BBP) is to allow users to simulate broadband (0–50 Hz) ground motion waveforms for complex earthquake ruptures using a variety of numerical modules modeling source, path and site effects. The BBP software is freely available for download and is designed to be used by both science and engineering researchers with some experience interpreting ground motion simulations. A large-scale validation exercise started in early 2012 and a first round of validation was completed in August 2013 for a subset of simulated events, for several simulation methodologies. This validation exercise is a multi-year project involving many stakeholders and the participating seismologists, engineers, programmers and users are referred to as the BBP Validation Team. The validation has been focused so far on pseudo-spectral acceleration (PSA) and consists of two complementary approaches: Part A involves comparison of simulated ground motions with recordings from past earthquakes and Part B compares median ground motion prediction equation (GMPE) results for hypothetical earthquakes with the median prediction from the BBP methods. While most of the BBP methods produce time series, the evaluation procedures for validation are geared toward

engineering-based metrics such as aggregate goodness-of-fit for average horizontal component PSA. Additional statistical and visualization tools have been integrated into the BBP to ensure uniform results for the evaluation, which determines distance and frequency ranges for which each method is considered to be reliable. The focus of the presentation is to highlight the key features of the BBP and of the validation methodology, and to introduce sample results considered in the evaluation.

Site-Specific Response in Validation Studies of Physics-Based Earthquake Simulations

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Although site response has long been known to be an important factor in modifying seismic motion, its integration in physics-based earthquake simulations is constrained by challenges of computational cost, and by the scarcity of geotechnical information; in turn, site response is accounted for in terms of trends through Vs30-based amplification factors. However, as the computational capabilities of 3D physics-based earthquake simulations extend in the high frequency range (>1 Hz), the fine resolution of the geotechnical layers and their nonlinear response have become increasingly important for validation studies. Recent efforts by the United States Geological Survey (USGS) have produced geotechnical profiles at more than 100 stations in Southern California. In this study, we use a subset of these profiles to perform site-specific analyses at stations used for the validation of physics-based ground motion simulations of the 2008 Chino Hills earthquake; and compare our results to recorded and physics-based simulated ground motions without site-specific response. We quantify the differences of ground surface predictions and observations in terms of both seismological and engineering intensity measures. We show that the goodness-of-fit of high frequency predictions compared to the recorded motions improves significantly when we introduce site-specific geotechnical profiles. Our results thus promote the interdisciplinary efforts of seismologists and engineers to introduce broadband simulated ground motions in earthquake design practice.

Some Modifications to Parameters used in the Stochastic Method for Simulating High-Frequency Ground Motions

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The stochastic method is widely used to compute ground motions at frequencies of engineering interest, for both point-source and extended-source fault representations. Since its introduction by Hanks and McGuire in 1981 and the enhancements to the method described by Boore in 1983, the method has changed little. Here we discuss several modifications and additions, not to the method, but to parameters used in many applications of the method. First, we have recently developed two generalized 2-corner-frequency source models that allow the specification of the high-frequency spectral level in terms of a parameter having the units of stress; this differs from other 2-corner-frequency models, in which the high-frequency spectral level is not a free parameter. Other modifications include: the crustal amplifications used for a generic rock velocity profile, for which the usual amplifications have been changed by up to 30%; the introduction of a finite-fault adjustment factor to capture the effect of a finite fault in point-source simulations; revisions to the random-vibration theory parameters used to estimate the ground-motion intensity measures; and a new relationship for the duration of shaking with distance in active tectonic regions. Most of this talk will be devoted to the last topic, which includes a clarification of which measure of duration corresponds to the duration of excitation of the simulation. The standard model of the path-dependent duration (in s) in active tectonic regons has been 0.05R (R in km; the total duration is the sum of the source and path durations). Durations computed from the NGA-West 2 database show that 0.05R underestimates the duration, often by more than a factor of two. The new path duration, estimated by subtracting the source duration from the observed durations, is a magnitude-independent, piecewise-linear function of distance.

Comparison of 3D and 1D Wave Propagation Modeling in the San Francisco Bay Area

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We performed 1D and 3D ground motion simulations in the San Francisco Bay area using kinematic rupture models for the M6.9 Loma Prieta earthquake, and M6.7 scenario earthquakes on the Hayward fault.

The objective of our investigation is to evaluate three-dimensional wave propagation effects on ground motion from large earthquakes in an area with complex underground structure, and compare the efficiency of 3D and 1D velocity models, at capturing such effects in the period range of 0.5 to 20 s. We use a deterministic approach for modeling wave propagation, and a combination of deterministic and stochastic approaches for rupture and velocity model parameterizations. A suite of rupture scenarios with stochastic slip variations was used to analyze the sensitivity of 3D and 1D wave propagation effects to small-scale variations in the rupture kinematics. The rupture models for both earthquakes were generated on the SCEC Broad-Band Ground Motion Simulation Platform using the Graves and Pitarka (2010) method. The simulations were performed in the frequency range of 0.01 to 2 Hz using an anelastic 3D finite-difference method and the USGS San Francisco Bay area 3D velocity model, Version 8.3.0, with surface topography. We added small-scale random perturbations to the original USGS velocity model to account for seismic wave scattering caused by structural heterogeneities. Strong motion data from the USGS and the California Geological Survey strong motion arrays were used in the models validation.

We will show results of our analysis using waveform comparison, and goodness of fit of spectral responses between simulated and recorded ground motion, as well as between 3D and 1D simulated ground motions, with respect to spectral period, fault distance, basin depth, and rupture scenario in the period range of 0.5 to 20 s.

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The Shakeout Earthquake Scenario with Plasticity

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Computer simulations of large ($M \geq 7.5$) earthquakes rupturing the southern San Andreas fault from SE to NW (e.g., ShakeOut, widely used for earthquake drills) have predicted strong long-period (> 2 s) ground motions in the densely populated Los Angeles basin. These amplifications are related to channeling of seismic waves trough a series of interconnected sedimentary basins, which result in a waveguide effect that has also been identified in virtual earthquakes constructed from the ambient seismic field.

However, predictions based on viscoelastic simulations or observations of ambient noise both assume a linear stress-strain relationship in crustal rocks and sedimentary deposits. We investigate the influence of nonlinear material behavior on ground motion levels by simulating the ShakeOut scenario (based on the kinematic source description of Graves et al., 2008) for a medium governed by Drucker-Prager elastoplasticity.

To account for the uncertainty in the yield strength of the propagating media, we experiment with three different models covering a broad range of possible cohesions, basing our choices on petroleum industry equations and published laboratory results. We also analyze the sensitivity of simulated shaking levels to the definition of the initial stress field.

Our results indicate that nonlinear material behavior could reduce the earlier predictions of large long-period ground motions in the Los Angeles basin by 30–70% as compared to viscoelastic solutions. These reductions are primarily due to yielding near the fault, although yielding may also occur in the shallow low-velocity deposits of the Los Angeles basin if cohesions are close to zero.

Fault zone plasticity remains important even for conservative values of cohesions, suggesting that current simulations assuming a linear response of rocks are overpredicting ground motions during future large earthquakes on the southern San Andreas fault.

PRENOLIN Project: A Benchmark on Numerical Simulation of 1-D Non-Linear Site Effect. 2 – Preliminary Results from the Verification Phase on Idealistic Cases

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The main objective of the PRENOLIN project is the assessment of the uncertainties associated to non-linear simulation of 1D site effects. An international benchmark is underway to test several numerical codes including various non-linear soil constitutive models to compute the non-linear seismic site response. A preliminary verification phase (i.e. comparison between numerical codes on simple, idealistic cases) will be followed by a validation phase comparing the predictions of such numerical estimations with actual strong motion recordings obtained on well-known sites. The benchmark presently involves 23 different teams and 28 different non-linear computations.

We present here the preliminary results of the verification benchmark dealing with ideal cases. Three different idealistic soil profiles were tested in a wide strain range with different input motions and different boundary conditions at the sediment/bedrock interface. A first iteration was organized in order to ensure a common understanding and identical results in the elastic and visco-elastic cases, and to identify the issues with the non-linear modelling. An ongoing second round of computations will provide a first quantification of the epistemic uncertainties linked with NL modelling with different NL rheological models. The analysis of the results from the first iteration show that the main discrepancies between numerical results can be attributed to (1) minor mistakes in input parameter implementation or output units, (2) different understanding of the expression "input motion" in different communities and (3) numerical dispersion and/or attenuation implementation. The first two points were clarified for the next iteration of the verification phase, which will focus on the implementation of the non-linear models.

PRENOLIN is part of two larger projects: SINAPS@, funded by the ANR, the French national research agency, and SIGMA, funded by a consortium of nuclear operators (EDF, CEA, AREVA, ENL).

Rupture Dynamics and Ground Motions from 3-D Dynamic Rough-Fault Simulations of Dip-Slip Events

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We perform 3-D numerical simulations of dynamic rupture along rough dip-slip faults to study the properties of rupture dynamics and patterns of resultant ground motions in dip-slip events. Shi and Day (2013) deterministically generated high-frequency ground motions for up to ~10 Hz by numerically modeling rupture propagation along a rough strike-slip fault. Dynamic rupture propagation on rough faults results in rupture irregularities that lead to ground motions with complex spatial patterns and extensive high-frequency content. The site-averaged synthetic response spectra have characteristics, including the distance and period dependence of the median values, absolute level and intra-event standard deviation, comparable to appropriate empirical estimates, throughout the period range 0.1-3.0 sec. In the current study we apply the methodology of Shi and Day (2013) to the deterministic simulation of high-frequency ground motions for dip-slip events by assuming that the surface topology of the dipping fault follows a self-similar roughness pattern. We explore the influence of geometrical and dynamic parameters of faulting on properties of rupture dynamics and ground motions. Parameters explored include fault dip, rake angle, depth to the top-of-rupture and stress distribution, with the goal of better understanding how ground motion phenomena such as directivity and hanging-wall amplifications are related to the dynamic and geometrical characteristics of dip-slip events.

High-Complexity Deterministic Q(f) Simulation of the 1994 Northridge Mw 6.7 Earthquake

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With the recent addition of realistic fault topography in 3D simulations of earthquake source models, ground motion can be deterministically generated more accurately up to higher frequencies. The synthetic ground motions have been shown to match the characteristics of real data, having a flat power spectrum up to some cutoff frequency (Shi and Day, 2013). However, the earthquake source is not the only source of complexity in the high-frequency ground motion; there are also scattering effects caused by small-scale velocity and density heterogeneities in the medium that can affect the ground motion intensity. Here, we dynamically model the source of the 1994 Mw 6.7 Northridge earthquake using the Support Operator Rupture Dynamics (SORD) code up to 8 Hz. Our fault model was input into a layered velocity structure characteristic of the southern California region characterized by self-similar roughness from scales of 100 m up to the total length of the fault. We extend the ground motion to further distances by converting the output from SORD to a kinematic source for the finite difference anelastic wave propagation code AWP-ODC. This code incorporates frequency-dependent attenuation via a power law above a reference frequency, and we illustrate the importance of including Q(f) in ground motion estimation. For example, a power-law exponent of 0.6 can produce up to a factor-of-two increase in the Arias Intensity compared to a constant-Q 0–2.5Hz simulation. We model the region surrounding the fault with and without small-scale medium complexity, with varying statistical parameters. Furthermore, we analyze the effect of varying both the power-law exponent of the attenuation relation and the scale factor relating Q and media velocity, and compare our synthetic ground motions with observed accelerograms. Additionally, we calculate the intra-event variability, i.e. the single-station standard deviation, and compare with values from leading Ground Motion Prediction Equations.

Using Attenuation in Ground Motion Prediction Equations: Validating Improvements to Strong Ground Motion Predictions

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We have recently developed a lithospheric attenuation model of North America in which we estimate the attenuation quality factors (Qp and Qs) for the crust and upper mantle over a broad frequency band (0.5–10 Hz). The attenuation model can be used to improve strong ground motion predictions, as had been previously demonstrated for the 2011 Mineral, VA earthquake. In order to make them easier to test, the models are incorporated into standard 1D ground motion prediction equations (GMPEs), effectively making them 2-D. Here, we test our ability to improve ground motion estimates for a much larger validation dataset of earthquakes in central and eastern North America compiled for the NGA-East. This dataset is a diverse set of recordings with a range of magnitudes, distances, tectonic settings, earthquake mechanisms, and ground motion levels. The use of attenuation models in GMPEs improves our ability to fit strong ground motions in the region, sometimes significantly, and should be incorporated in future national hazard maps.

Constraining GMPEs in Critical Ranges for Complex Ruptures Using Strong Motion Simulation Procedures on the SCEC Broadband Platform

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As a part of the Southwestern U.S. (SWUS) Ground Motion Characterization (GMC) SSHAC Level 3 study for the Diablo Canyon Power Plant (DCPP), broadband ground motion simulations have been performed for a variety of scenario and validation earthquakes using the Southern California Earthquake Center (SCEC) Broadband Ground Motion Simulation Platform (BBP). A BBP user generates broadband ground motions using physics-based simulation methods by prescribing fundamental earthquake scenario parameters. The first validation phase of the BBP was recently evaluated by Dreger et al. (2013) for simulated pseudo-spectral acceleration (Sa) using version 13.6.1 of the BBP code. Using the validated version of the BBP, we address the hazard-significant technical issue of how several critical Ground Motion Prediction Equation (GMPE) input parameters are best defined in important ranges for complex ruptures; areas where there is very little recorded data. We define 'complex' ruptures as those having a significant change in strike, rake, or dip along strike. We also consider a set of 'splay' ruptures, which we define as one main fault with a secondary branching fault. Simulations are evaluated for three complex and two splay scenarios over the range Mw 7.0 to 7.4. The changes in geometry and faulting style are located near the site of interest, where the definition of many GMPE input parameters (including dip, rake, depth, distance, magnitude etc.) is unclear. Using nine GMPEs developed for active tectonic regions, we show that the differences in these selections can have a significant impact on the predicted ground motion levels. We present multiple methods for defining GMPE input parameter rules, and these multiple methods are compared with the response spectra obtained using the three BBP simulation techniques validated by Dreger et al. (2013). Note that these simulations are an aid

for improving GMPE implementation and are not representative of realistic hazard levels for the area.

The Effect of Topography on the Seismic Wavefield

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We perform a series of seismic wavefield simulations in 3D structural models in order to quantify the effect of topography on seismic waveforms. Our procedure involves three components: (1) constructing a finite-element, unstructured hexahedral mesh, (2) performing seismic wavefield simulations, and (3) quantifying differences between seismograms. We consider three different structural models: homogeneous, layered, and realistic 3D variations. For each structural model we produce a mesh with and without topography. For each of these meshes we produce a finer version in order to demonstrate the minimum resolvable period for the coarser meshes. The target regions are southern California and Alaska, both of which exhibit large topographic variations and also have abundant seismic stations that allow for comparisons with recorded data. Our simulations shows that the topography has the strongest effects on surface waves, whereby a phase shift of the main arrival occurs due to the different thickness of the uppermost layer (which includes the topography or not). Scattered waves are visible in the coda due to surface wave reflections that occur off the direct source-station path. Our analysis emphasizes seismograms with periods $>= 1$ s, with the motivation to understand the topographic signatures that may influence measurements used within adjoint-based tomographic inversions with earthquake data.

Long-Period Ground Motion Simulation for the 2007 Chuetsu-oki, Japan, Earthquake using the Ambient Seismic Field

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After the 2011 Tohoku earthquake, the Japanese government re-evaluated source regions of megathrust potential, and the need for seismic hazard assessment for long-period ground motions is increasing. Deterministic numerical simulations have been used for long-period ground motion prediction for decades. Here we take an alternative approach of simulating long-period ground motion using the ambient seismic field. Long-time correlation of ambient field has been demonstrated as a useful tool for strong ground motion prediction (Prieto and Beroza, 2008; Denolle et al., 2013, 2014). An advantage to applying this approach in Japan is that ambient-field sources are active in diverse directions. The dominant period of the ambient field for the NIED/F-net datasets is mostly 7 s over the year, and amplitudes are largest in winter. This period matches the dominant periods of the Kanto and Niigata basins. We explore the applicability of ambient field Green's function simulation of long-period ground motions for the 2007 Mw 6.6 Chuetsu-oki crustal earthquake, which excited large surface waves in and around the Kanto basin almost 200 km from the epicenter. We use three components of F-net broadband data at KZK station, which is located near the source region, as a virtual source, and three components of six F-net stations in and around the Kanto basin to calculate the response in a period range of 4–20 s. We use corrections for source depth and focal mechanism proposed by Denolle et al. (2013). Long-period ground motions by numerical simulations largely rely on 3-D velocity structure models. Current national models are limited to 1 km spatial scale with minimum Vs of 350 to 500 km/s. Even though ambient field Green's functions may contain artifacts in amplitude due to an uneven source distribution, paired with installations of ocean bottom seismometer network, they will provide essential information for anticipating the effects of future megathrust events.

Validation of the Equivalent Point-Source Method for Modeling Ground Motions from Large Earthquakes

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A common observation, as captured in empirical ground-motion prediction equations, is that the distance-scaling of ground motions saturates at close distances to large earthquakes. Conventional point-source models cannot mimic this behavior because the total energy is assumed to be released from a single point, leading to monotonically increasing ground-motion amplitudes with decreasing distance. However, the performance of point-source models can be improved by defining a modified (or 'equivalent') distance at which the point source is considered to occur, such that ground motions are correctly predicted at close distances. This approach is referred to as equivalent point-source modeling.

In this study, we examine the ability of the equivalent point-source approach to describe ground motions from large earthquakes, particularly at close distances. We model the source and attenuation attributes of a suite of well-recorded $M \geq 6$ earthquakes based on the equivalent point-source method, considering also parameter trade-off issues. We select the best-fitting attenuation model for each earthquake by regression analysis, using the residual statistics as a statistical constraint, and the known seismic moment as a physical constraint. We develop a model for the magnitude dependency of distance-saturation effects observed in Fourier amplitudes, using the results obtained from study events. We conclude that equivalent point-source models can successfully predict the average motions from large earthquakes, and replicate the close-distance saturation effects seen in recorded ground motions. This is a useful conclusion as it lays the foundation for simplified modeling of expected ground motions in regions such as eastern North America, where empirical ground-motion data from large events are lacking.

Merging Paths: Earthquake Simulations and Engineering Applications

Oral Session · Thursday · 3:45 PM · 1 May · Room 3 Session Chairs: Ricardo Taborda, Aysegul Askan, and Tsuyoshi Ichimura

Simulation of Structure Seismic Response Based on Analyzing Fault-structure System in Large Computing Environment

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Many physics-based earthquake simulation tools are increasingly being employed for site-specific ground motion estimation – owing to the continuous advancement in computation power, improvements in characterization of underground crust structures and availability of fault information. In the engineering field, such tools can be used to improve earthquake damage prediction to critical structures or buildings in urban area. In this study we conducted a fault-structure system analysis (combined earthquake simulation and analysis of building structure seismic response): the geologic-length scale processes are solved in the first step, and the second step analyzes engineering-length scale processes using the results in the first step as input boundary condition. In order to realize the computation in the first step within the range of frequencies relevant to engineering applications, we developed a parallel earthquake simulator suited to multicore computers. This simulator consists of parallel hybrid-grid mesh generator and a solver based on implicit time integration scheme. To utilize the architecture of large computers such as the K computer in Japan, the solver is implemented with MPI/OpenMP parallelization. For the structure response analysis, we consider a small region which includes building structures and local soil. As a preliminary test, we considered a M_w 6.4 scenario earthquake near the city of Niigata in Japan. First, we generated the crust model in K computer. Then we created the force data based on modeling the fault rupture using multiple point sources with varying starting times. For the soft soil response analysis, a fine-meshed model of a region under the city was generated. The results were inputted as base excitation to a structure seismic response analysis tool, Integrated Earthquake Simulator. We compared the response of several buildings based on case examples highlighting the advantage of three-dimensional ground motion modeling.

End-to-End Simulation of the Response of Building Clusters During Earthquakes in the Presence of Coupled Soil-Structure Interaction Effects

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We present results from various end-to-end simulations synthesizing the earthquake fault, regional ground motion, and local response of building clusters during earthquakes, including the presence of coupled soil-structure interaction effects. Simplified structural models are used to represent the buildings arranged in regular, homogeneous building clusters. We consider various clusters with different number of buildings, building heights and separations. This parametric approach is possible thanks to the use of a two-step finite element simulation procedure that allows us to vary the cluster arrangements and building types as many times as needed, while simulating the regional ground motion only once. The simulation corresponds

to a model of the San Fernando Valley during the 1994 Northridge earthquake. Through the simulations, we seek to characterize the coupling effects between the soil, the foundation, and the structural response of individual buildings in the presence of surrounding structures. To that end, we focus on the structural response of the building at the center of the clusters. We also obtain the response of this building in isolation (that is, without the presence of additional structures), and with and without soil-structure interaction effects. This allows us to disaggregate the different system-component contributions to its structural response. Our results indicate that the soil-structure interaction and coupling effects in the systems vary depending on the number and dynamic properties of the buildings, their separation, and the impedance with respect to the soil, and reveal interesting group effects.

City-Soil Interaction in the Valley of Mexico: Amplification and Long Duration Ground Motion

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We present a study of the built environment on the wave-fields that result from earthquakes in Mexico City. Even though the ground motion due to earthquakes in the city primarily originates in strong but distant sources, the amplification and long duration of the records in the Lake Zone versus rock sites can be several orders of magnitude larger. Several mechanisms have been proposed to explain the anomalous ground motion in the Valley of Mexico (VM), e.g. gravity waves, city-soil interaction, and effects induced by the local and regional geological structures. We analyze the influence of buildings on the wave-field using numerical simulations with a $f < 1$ Hz resolution and low shear wave velocities of 50 m/s. The simulations use a realistic model of the VM built using information from geophysical and geotechnical experiments, and embedded into a regional model. The ~1.5 million buildings used in our computations are derived from the available inventories of the Mexican Federal District's counties, LIDAR data, and empirical rules to determine their elastic properties. The wave propagation is computed using a highly efficient octree-based finite element implementation (Tu et al., 2006) for near (intraslab) and distant (interplate) earthquakes, the June 16th 2013 Mw=5.8 and March 20th 2013 Mw=7.4, respectively. We observe that the presence of the structures substantially modifies the amplification of the ground motion, compared to the simulations excluding the city. In general, the ground motion parameters are lower. More importantly, we observe highly variable increments in the duration, especially in the Lake/Transition Zone west of the city, where the density of the built environment is higher compared to the rest of the city.

Nonlinear Time History Analyses of Structures Under Real and Synthetic Ground Motions

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Full time series of ground acceleration is required for nonlinear time history analyses which are employed for evaluating the dynamic response of a structure under earthquake excitations. For regions with sparse ground motion data, alternative ground motion simulation techniques are used to generate acceleration time series with varying levels of accuracy. While using simulated records for engineering purposes, it is critical to investigate the efficiency of these records in predicting the real engineering demands. In the first part of this study, nonlinear time history analyses of 9 typical multi-story reinforced concrete frame structures are performed to compare structural responses to synthetic records with those to the real ground motions of a particular event. The 2009 L'Aquila (Italy) (Mw=6.3) earthquake is simulated using two alternative simulation methods: Hybrid Integral-Composite method and Stochastic Finite-fault method. Results of nonlinear time history analyses from the real and synthetic records of the mentioned event are compared in terms of maximum displacement of each story levels. We observe that the stochastic finite fault method is found to be more conservative in predicting the seismic responses of RC frame structures for this specific case. In the second part of the study, to further test the validation of the Stochastic Finite Fault method in prediction of real dynamic responses, 1992 Erzincan earthquake (Turkey) (Mw=6.6) is considered. For this second event, results show that for cases where near-field or basin effects are of concern, Stochastic Finite Fault method may not sufficiently predict real responses.

Rupture to Rafters to Response: Completing the Loop of Earthquake Science, Engineering and Policy

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Ground motion definition is the link between seismic hazard and structural response, the first two elements of performance-based earthquake engineering. Site- and structure-specific ground motion selection is enabled by improved ground motion prediction and considerations of important seismic parameters for nonlinear dynamic analyses. Ground motion databases are growing, with denser instrumentation that provides more empirical recordings, high performance computing that facilitates large-scale simulations, and breakthroughs in geophysical understanding that push the frontiers to the high-frequency range. Structural models are also evolving with enhanced accuracy and complexity to capture important structural behaviors such as collapse, cumulative damage and 'in-cycle' strength and stiffness degradation. In the past decade, significant progress has been made in the performance-based earthquake engineering framework to interpret structural performance results in terms of structural response, damage and loss. At the same time, Great ShakeOut Earthquake Drills are extending beyond California to improve earthquake preparedness, with over 24.7 million participants worldwide in 2013. The advancements in hazard characterization, structural modeling, performance interpretation, and emergency response offer a unique opportunity to integrate these elements to complete the loop of earthquake science, engineering and policy to reduce risk.

Alaska Update of the USGS National Seismic Hazard Maps

Oral Session · Thursday · 8:30 AM · 1 May · Room 4

Session Chairs: Peter Haeussler, John Anderson and Mark Petersen

Challenges Facing the Update of the 2007 Probabilistic Seismic Hazard Map of Alaska and the Aleutians

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The revision of the 2007 USGS PSHA map of Alaska and the Aleutians presents challenges unique to Alaska as well as those common to many PSHA efforts. The geologic and geophysical assumptions underlying the 2007 map require review and new ground motion models and their applicability to Alaska need to be considered. While geologic data on earthquake recurrence in Alaska continues to emerge, there is considerably less information available than in California and other seismically active portions of the United States. Particularly thorny issues relate to the segmentation or lack thereof, and the recurrence model to be used for the Alaska-Aleutian megathrust, the Denali, the Fairweather-Queen Charlotte, Castle Mountain, and other long active fault systems. Incomplete identification of active faults, lack of information on activity of the Tintina fault system, and poor understanding of the tectonics and sources of earthquakes in central Alaska contribute to uncertainty. The role of aseismic slip in possibly limiting earthquake potential along the megathrust needs to be revisited, as do the implications of slip-partitioning on the earthquake potential at the far western end of the arc. Marine seismic surveys indicate that the Transition Fault is characterized by strike-slip rather than thrust motion as assumed in 2007, and the tectonic model of the so-called Yakataga Gap needs to be revisited in the light of recent studies.

Updating the USGS Seismic Hazard Maps for Alaska

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The U. S. Geological Survey (USGS) plans to update the national seismic hazard maps for Alaska beginning in 2014. The maps show probabilistic, time-independent ground motions for building codes and other applications. The current maps were developed in 2007 (Wesson and others, USGS Open-File Report 2007–1043). For the new maps we will revise and extend the earthquake catalog; update source models for the Alaska-Aleutian megathrust fault, several crustal faults, and seismicity-based sources; and implement new ground-motion-prediction relations. In 2007 the megathrust was modeled as a segmented dipping plane, with segments largely controlled by past great earthquakes, and recurrence estimated from seismic history rather than plate rates. The update will incorporate new thinking on

megathrust geometry, segmentation, and recurrence. In 2007 crustal faults in the model included the Fairweather-Queen Charlotte system, the Denali-Totschunda system, the Castle Mountain fault, crustal faults on Kodiak Island, and the Transition fault, with recurrence estimated from geologic and paleoseismic data. The update will incorporate an important new resource: the Quaternary fault database recently developed by the Alaska Division of Geological and Geophysical Surveys. Recurrence, geometry, and maximum-magnitude models for crustal and Benioff-zone seismicity sources will be updated using the new catalog and seismicity statistics. We are hopeful that geodesy will play a greater role in the update. Improved ground motion equations for crustal and subduction earthquakes will include NGA-West2 and BCHydro; in particular, new relations for subduction earthquakes use major datasets from recent great earthquakes in Japan and Chile. As in 2007, we also plan to make time-dependent hazard maps that explicitly account for the elapsed times since past earthquakes.

The Denali Fault Slip Rate and Models of Interior Alaska Active Deformation

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The neotectonics of southern and central Alaska are characterized by a several-hundred km-wide zone of right-transpressional deformation across the Alaska Range and the Cook Inlet region. The Denali fault system (DFS) is by far the largest of these active strike-slip fault systems and produced the 2002 M7.9 Denali fault earthquake. Previously, we used surface-exposure cosmogenic nuclide dating to show that the Quaternary slip rate decreases westward along the central 275 km of the fault system from about 14 to 9 mm/yr. New cosmogenic slip rate data at Ripsnorter Creek shows a slip rate of about 5 mm/yr on the western Denali fault. On the eastern Denali fault near Kluane Lake, Yukon we infer a slip rate of about 3–4 mm/yr from offset geomorphic features and the estimated age of deglaciation. These data imply the highest slip rate near the intersection of the Denali and Totschunda faults and a decreasing slip rate to the east and west. The Denali fault system is transpressional with active thrust faults both to the north and south. Those to the north parallel the fault, in contrast to those to the south that branch off it. We infer the southern thrust faults accommodate lateral slip, resulting in the westward decrease in slip rate on the DFS. Models of deformation of southern Alaska can be considered as having a range between two end members, with different implications for seismic hazards. One is a purely rotational model where the region south of the DFS, the southern Alaska block, rotates counterclockwise; in this case hazard is concentrated along the DFS. Another is an indenter model, where the southern Alaska block is moving northwestward and not rotating, resulting in widely distributed hazard on both the DFS and thrust faults. We favor a combination of indentation, rotation, and internal deformation of the southern Alaska block to explain the slip rate on the DFS and the distribution and geometry of thrust faults north and south of the Alaska Range.

Recurrence of Large Earthquakes Along the Denali Fault System

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The Denali fault system (DFS) is the major active crustal structure of interior Alaska and the source of the M7.9 2002 Denali fault earthquake. Evidence obtained since 2002 of the timing of paleoearthquakes at 17 locations along the DFS between Denali National Park, AK and Kluane Lake, Yukon Territory provides preliminary characterization of DFS recurrence. 1) At least four large earthquakes occurred along the 2002 Denali-Totschunda rupture section during the past ~1300 years. Of these, the Denali penultimate rupture occurred between 350–570 yrb02 (radiocarbon calibrated years before 2002) and is more recent than the Totschunda penultimate event, which occurred 580–735 yrb02. The third event back on the Denali, 705–1070 yrb02, pre-dates the third back event on the Totschunda at 1180–1390 yrb02. 2) On the eastern Denali the most recent event (MRE) and penultimate ruptures occurred between 100–350 yrb02 and shortly before 600–700 yrb02, respectively. 3) The Denali west of the 2002 rupture contains geomorphically fresh scarps; its MRE likely occurred within the past 250 years and the penultimate event was between 570–680 yrb02. These observations suggest the DFS is a segmented system that includes the 2002 rupture, segments west and east of the 2002 rupture, as well as the Totschunda fault, with each capable of rupturing independently or, as occurred in 2002, failing together. Recurrence of large earthquakes at any point along the DFS in Alaska east of Denali (Mt. McKinley) is approximately 400–650 years; Yukon section intervals are longer, averaging 1000 years. If presently identified segments remain essentially independent the average recurrence for a large rupture somewhere along the DFS is about 125 years. Structural isolation, a relatively high slip rate (9–15 mm/yr), and recurrence and slip/event observations suggest that the recent behavior of the DFS is consistent with both time and slip-predictable recurrence models.

Synthesis of Results from a Transect of Paleoseismic Investigations Across the Alaska Range

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Recent recognition of previously unknown active faults in the Alaska Range of south-central Alaska has contributed to an evolving understanding of the neotectonic framework of the Denali fault system and south-central Alaska. As a strain-partitioned transpressional orogen, the Alaska Range is dominated by the right-lateral Denali fault and Denali-fault parallel thrust faults that accommodate shortening across the range. To document seismic hazards and constrain fault system behavior, we have undertaken paleoseismic investigations on all 5 active fault zones that intersect the Parks Highway/Nenana River corridor through the Alaska Range. We have excavated a total of 11 paleoseismic trenches across 5 active fault traces, specifically the Denali fault, Hines Creek fault (aka Park Road fault), Healy fault, Healy Creek fault, and Northern Foothills thrust. Except for the Denali fault, these were the first paleoseismic studies on these faults. All faults display evidence for Holocene surface-rupturing earthquakes, and we have clearly defined evidence for multiple late Holocene earthquakes on the Denali fault and Hines Creek faults. All faults along this transect require additional research for full seismic hazard documentation and each fault trace possesses potential for fruitful future studies. The Healy Creek fault, its stepover to the Stampede fault, and the Northern Foothills thrust notably require additional paleoseismic investigations to constrain the most recent event. However, with the long history of regional tectonic interpretations of southern Alaska based upon limited data, any new control on paleoearthquake occurrence and slip rates for active faults in this region has the potential to provide substantial contributions to regional tectonic understanding in addition to potential hazards.

Implications of Recent Paleoseismic Observations for Models of Alaska-Aleutian Megathrust Rupture Patterns

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Here we summarize post-2007 paleoseismic observations along the Alaska-Aleutian megathrust and suggest that the next update of the USGS National Seismic Hazard Map (NSHM) for Alaska allow for a greater variety of multi-segment ruptures, revisit maximum magnitudes (Mmax), and relax the assumption that segment boundaries match historical rupture boundaries.

The 2007 NSHM model allowed a characteristic M 9.2 earthquake with 650-year recurrence to rupture the Kodiak and Prince William Sound (PWS) segments. Recent work by Shennan et al. (2009) suggests that the Yakataga and PWS segments have ruptured together, and that the NSHM update should consider alternate multi-segment ruptures supported by paleoseismic data.

The 2007 model fixed the 1964 rupture boundary between the Kodiak and Semidi segments. Our observations at Sitkinak Island of the 1964, 1788, and earlier ruptures suggest that this boundary may not persist at time scales relevant for hazard calculations.

Our observations at Chirikof Island suggest that the Semidi segment has generated tsunamis every 250–400 years for the past ~3.4 ka, but it is not yet clear if the 1938 M 8.2 rupture released more or less moment than the 1788 rupture. This is important for time-dependent calculations and for re-evaluation of Mmax=8.5 for the Semidi segment.

At Simeonof Island in the Shumagin segment, we find no geologic evidence for sudden coastal uplift or subsidence or for inundation from large tsunamis since ~3.4 ka. Although elastic dislocation models permit ruptures of up to M 8.5 trenchward of the island, an absence of high tsunami deposits on Simeonof implies such models are unlikely.

Finally, tsunami deposits at Sedanka and Umnak Islands suggest 280–320 yr recurrence of heterogeneous ruptures in the area of the 1957 M 8.6 earthquake. Uncertainty in past rupture behavior in the western Aleutians segment supports continued use of truncated Gutenberg-Richter behavior until more specific rupture patterns are defined.

GPS-Derived Fault Geometries and Slip Rates for Eastern Prince William Sound and the St. Elias Orogen

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The region between Prince William Sound and Yakutat Bay has generated several major earthquakes in recorded history, including the M9.2 1964 Alaska earthquake, the M7.3 1979 St. Elias earthquake, and the M8 1899 earthquake that occurred in the vicinity of Cape Yakataga. Detailed geodetic estimates of geometries and slip rates for the faults involved in these events have been limited by the sparseness of the available data. We use data from nearly 70 campaign and continuous GPS sites to estimate slip rates and fault geometries for faults throughout the region.

Our results suggest that a shallowly dipping (5 degrees) locked subduction interface between the Yakutat block and southern Alaska underlies the area from Prince William Sound to the eastern side of the Bering Glacier. This estimate of the locked extent of the interface reaches further east and inland than previous geodetic estimates and agrees with paleoseismic studies that suggest that past megathrust events ruptured further east than the 1964 earthquake. The interface underlying areas inboard of the coast appears to be fully locked, with slip deficit rates of 45–50 mm/yr. The interface underlying the coastal margin and the offshore regions is partially locked, with slip deficit rates of 20–35 mm/yr. The exception is the area northwest of Cordova, which is fully locked with a slip deficit rate of 50 mm/yr. To the east of the Bering Glacier, the subduction interface appears to be creeping, with the exception of a small locked region to the north of Mount St. Elias that coincides with the epicenter of the 1979 event. Above the eastern interface, there are several crustal thrust faults that likely sole out into the decollement. Together, these faults accommodate nearly 40 mm/yr of convergence within a relatively narrow region near the coast. The fault system with the largest slip deficit rate (20–25 mm/yr) runs through the Yakataga area and continues offshore, posing potential tsunami hazards.

The Castle Mountain Fault, South-Central Alaska: Sense of Slip and Slip Rate

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The Castle Mountain fault extends along the southern Talkeetna Mountains range front and across the Susitna Lowland, presenting a major seismic hazard to the city of Anchorage, Alaska, and the surrounding region. The 2007 update of the USGS National Seismic Hazard Map (NSHM) for Alaska assigned the fault a faster slip rate (0.5 to 2.9 mm/yr) and lower Mmax (7.5 to 7.1), resulting in a substantial increase in the seismic hazard from the 1999 map. In the Susitna Lowland the fault is expressed as a distinct south-facing scarp; however, paleoseismic studies are few and considerable uncertainty exists regarding the timing of past earthquakes, slip rate, and sense of slip. Here we present interpretations of LiDAR-derived topography and the results of field surveys that were conducted to re-examine the sense of slip and slip rate.

Between Houston and Susitna River, surficial geologic mapping indicates that the fault displaces late Elmendorf (14–15 ka) glacial and Holocene unconsolidated deposits with scarps varying in height from ~ 0.5–5 m. The surface expression of the fault includes left-stepping en echelon scarps and grabens located up to 400 m north of the scarp, indicating a wide zone of deformation. Numerous Holocene landforms oriented orthogonal to the scarp are vertically offset and have no discernible lateral displacement. These observations are consistent with reverse faulting above a north-dipping fault associated with bending-moment grabens in the hanging wall. Our observations conflict with the lateral sense of slip and slip rate presently used in the NSHM. We suggest that the fault may be more accurately characterized as a reverse fault, which is consistent with our field observations and the presence of a 4-km-wide anticline north of the fault. If our interpretation of dominantly reverse faulting along the Castle Mountain fault is correct, then displaced glacial deposits at >20 locations implies a Holocene vertical slip rate of ~0.5 mm/yr.

New Seismic Hazard Model for North-Western Canada

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The Geological Survey of Canada has recently completed the national seismic hazard maps to underpin earthquake loading provisions for the 2015 National Building Code of Canada. This process involved reassessment and revision of earthquake sources in the Canadian Arctic, northern British Columbia and adjacent Alaska. Area sources are defined through a multi-tiered approach in a GIS framework. The key thematic layers used to guide the classification of area sources are; historical earthquake epicentres; tectonic elements; gravity and magnetic anomalies; and multi-resolution topography and bathymetry.

For the first time, hazard from crustal faults in Yukon, and adjacent Alaska is calculated based on GPS- and paleoseismic-based slip rates. Maximum magnitude for each fault source is determined from published magnitude-area scaling relations. Hazard along the offshore Queen Charlotte and Fairweather faults is also now predominantly based on crustal deformation rates, with minor contributions to off-fault hazard from historical seismicity. In acknowledgement of the M_W 7.7 2012 Haida Gwaii thrust earthquake, we partition the slip between the strike-slip Queen Charlotte fault and the shallowly-dipping Haida Gwaii thrust source modelled as a subduction source.

A regional tectonic model, supported by GPS deformation rates and earthquake focal mechanisms (Leonard et al., JGR, 2007), suggests that observed northerly motion from Yukon continues to the Beaufort Sea margin. The inferred convergence in the Mackenzie Delta region could manifest itself through infrequent large earthquakes with very few small events. Based on this hypothesis, a new Beaufort-Mackenzie Convergence zone allows for the possibility of seismogenic thrusting (up to M_W 7.8) beneath the delta sediments.

Site-Specific Probabilistic Seismic Hazard Analyses of Anchorage, Alaska and Comparison to the 2007 National Seismic Hazard Maps

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We have been performing site-specific probabilistic seismic hazard analyses for sites located in Anchorage, Alaska. The city is situated in one of the most seismically active regions in the U.S. The Alaskan subduction zone, which underlies the city, was the source of the 1964 M 9.2 Great Alaska earthquake. Wadati-Benioff earthquakes within the subducting Pacific plate and nearby crustal faults could also generate future strong ground shaking in the city. Unlike the National Seismic Hazard Maps (NSHM), we consider all active and potentially active fault sources that could affect Anchorage. For example in the Anchorage area, the 2007 NSHMs included only the Castle Mountain fault as a crustal fault source because of the lack of fault studies in the region. The nearby Cook Inlet faults are characterized in our analyses based on the studies of Haeussler et al. (2002). The uncertainties for all fault parameters are handled through the use of logic trees. We quantify the uncertainties in the seismogenic capability of all faults by assigning probabilities of activity. Our characterization of the Alaskan subduction zone megathrust uses many of the parameters used in the 2007 NSHMs with some revisions based on recent paleoseismic studies. Unlike the NSHM's use of horizontal zones of gridded seismicity, we modeled the Wadati-Benioff zone as a dipping slab. We calculated recurrence for intraslab earthquakes in the historical catalog identified using the slab geometry. Both a uniform source zone and gridded seismicity were included in our probabilistic analyses. We used recent subduction zone ground motion prediction models (e.g., Abrahamson et al., 2013) and the NGA West-2 models. The intraslab zone dominates the PGA hazard. For long-period ground motions (e.g., 1.0 sec or more), the megathrust generally controls the hazard. We compare these site-specific hazard results in Anchorage to the 2007 NSHMs.

Seismic Imaging as USArray Moves to Alaska

Oral Session · Thursday · 1:30 PM · 1 May · Room 4 Session Chairs: Carene Larmat, Frank Vernon, and Bob Woodward, and Lindsay Worthington

Seismic Velocity Structure and Anisotropy of the Alaska Subduction Zone Derived from Surface Wave Tomography

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The Aleutian-Alaskan subduction zone is extremely active and driven by northwesterly subduction and collision of the Pacific/Yakutat plate. Better structural models of the crust and upper mantle are needed in order to constrain geodynamic models, which have examined the mantle flow at the eastern edge of the subduction zone. Tomographic studies have been performed based on short-period P and S body-wave traveltimes, either from local or global events, but Alaska structure remains unclear, partly because it has only been imaged from a small portion of the seismic wavefield. In this study, surface waves are used for the first time to investigate the structure of the Alaska-Yakutat-Wrangell subduction system at the eastern end of the Aleutian-Alaska subduction zone. Rayleigh waves are used within a two-plane wave representation with finite frequency sensitivity kernels to image the seismic velocity structure of the crust and upper mantle. The data set comprises 400 earthquakes Mw >= 6.0 at epicentral distances 30–120 degrees, and 168 broadband stations within Alaska (both permanent and temporary stations), for a total of 9865 source-station paths. Cross-correlation phase and amplitude measurements of Rayleigh waves over periods 22 s to 143 s provide maximal sensitivity to structures between in the depth range ~30–200 km. The 3D shear velocity model reveals a fast velocity anomaly associated with the subduction zone in the depth range of ~90–210 km and likely deeper. The onshore portion of the Yakutat block is associated with a slow anomaly at depths shallower than 70 km. Azimuthal anisotropy of phase velocity at 40 s shows an NW-SE fast direction in the Gulf of Alaska that continues into the backarc, which agrees with the convergence direction between the Pacific and North America plates. Anisotropy also shows abrupt fast direction change surrounding subsurface boundary of the Yakutat block, as identified by Eberhart-Phillips et al. (2006).

Seismic Imaging along a Dense Broadband Transect through Central Alaska

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Alaska has North America's longest and seismically active subduction zone. Over the last 15 years a series of broadband arrays have been deployed across its eastern end in central Alaska, including the Broadband Experiment Across the Alaska Range (BEAAR) and Multidisciplinary Observations Of Subduction (MOOS), together sampling a 450 km transect at 10–15 km spacing. The arrays provide scattered-wave migration images of the subduction zone. The rupture zone of the great (Mw9.2) 1964 earthquake shows a narrow low-velocity channel without thrust-faulting focal mechanisms, although abundant seismicity lies within the subducting plate. Where the subducting crust reaches mantle depths the thick low-velocity crust of the subducting Yakutat oceanic plateau is imaged. That seismically disappears at 130 km depth with eclogitization. Seismic attenuation shows 10–50× variations within the overlying mantle wedge. A cold high-Q forearc nose abruptly transitions where the plate interface reaches 80 km depth to low-Q, hot and presumably flowing asthenosphere, constraining thermal structure. Shear-wave splitting from arrays and others, from Pacific to Arctic coasts, show Alaska divided in two domains. Fabric rotates 90 degrees where the subducting plate is 80 km deep, i.e. where the mantle wedge transitions from cold to hot. The southern domain shows convergence-parallel fast directions for all plate depths, indicating sub-slab flow or fabric. The northern domain shows slab-parallel fast directions. Because delay times correlate strongly with thickness of the mantle wedge, a dominant component of the northern fabric comes from the mantle wedge, perhaps along-strike flow. However, that fabric continues far into North America where it parallels absolute plate motion. USArray will provide critical data to resolve the interaction between subduction- and plate-scale flow, to see the extent to which subduction leaves an imprint far inland from the trench.

Imaging the Megathrust Zone and Yakutat/Pacific Plate Interface in the Alaska Subduction Zone

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We image the subducted slab underneath a 450 km long transect of the Alaska subduction zone. Densely spaced stations in southern Alaska are set up to investigate (1) the geometry and velocity structure of the downgoing plate and their relationship to slab seismicity, and (2) the interplate coupled zone where the great 1964 earthquake exhibited the largest amount of rupture. The joint teleseismic migration of two array datasets based on teleseismic receiver functions (RFs) reveals a prominent, shallow-dipping low-velocity layer at ~25–30 km depth in southern Alaska. Modeling of RF amplitudes suggests the existence of a thin low-velocity layer (Vs of ~2.1–2.6 km/s) that is ~20–40% slower than underlying oceanic crustal velocities, and is sandwiched between the subducted slab and the overriding North America plate. The observed low-velocity megathrust layer may be due to a thick sediment input from the trench in combination with elevated pore fluid pressure in the channel. Both velocities and thickness of the low-velocity channel increase downdip in central Alaska, in agreement with previously published results. Our image also includes an unusually thick low-velocity crust subducting with a ~20 degree dip down to 130 km depth at approximately 200 km inland beneath central Alaska. The unusual nature of this subducted segment results from the subduction of the Yakutat terrane crust. We also show a clear image of the Yakutat and Pacific crust subduction beneath the Kenai Peninsula, and the along-strike boundary between them at megathrust depths. Our imaged western edge of the Yakutat terrane, at 25–30 km depth in the central Kenai along the megathrust, aligns with the western end of a geodetically locked patch with high slip deficit, and coincides with the boundary of aftershock events from the 1964 earthquake. It appears that this sharp change in the nature of the downgoing plate could control the slip distribution of great earthquakes on this plate interface.

Seismic Tomography of Alaskan Volcanoes: Accomplishments and Opportunities

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The Alaska Volcano Observatory (AVO) was established in 1988 as a cooperative program of the U.S. Geological Survey (USGS), the Geophysical Institute at the University of Alaska Fairbanks, and the Alaska Division of Geological & Geophysical Surveys. The primary objectives of the AVO seismic program are real-time monitoring of active hazardous Alaskan volcanoes and investigation of seismic processes associated with active volcanism. Most of the monitored volcanoes have small networks of 4 to 7 seismic stations, and the seismometers are primarily short-period, vertical-component. Network geometries are unfavorable in many cases due to logistics, and weather and funding limitations result in significant station down-time. Despite these challenges, AVO has collected a rich dataset that is suitable for a diverse suite of studies.

In 2004, with support from the National Science Foundation and the USGS, University of Wisconsin-Madison and AVO scientists began working together to improve the quality of the earthquake locations at particular volcanoes using the data collected by AVO over the years. One valuable aspect of this work is the ability to determine precise locations of possible precursory seismic activity relative to relocated catalog events in near-real-time, thereby enhancing AVO's monitoring efforts. In some cases, the data are also sufficient for body-wave tomography analysis. Several of these tomography studies built on previous work by AVO and other scientists, for example Benz et al. (1996) for Redoubt, Power et al. (1998) for Spurr, and Jolly et al. (2007) for the Katmai group. More recently, the availability of continuous seismic data has enabled the application of ambient noise tomography, with published work to date for Okmok and Katmai. I will provide an overview of these studies, including new work on joint body wave-surface wave tomography, and highlight some opportunities for future research as Alaska becomes a focus for EarthScope and GeoPRISMS.

Seismicity of Alaska 1973–2013: A Well-constrained Catalog of Earthquake Locations Using Multiple Event Relocation Methods

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The USGS National Earthquake Information Center (NEIC) used the Lawrence Livermore National Laboratory (LLNL) code Bayesloc to produce well constrained multiple event relocations of more than 10,000 earthquakes (complete to ~M4.5) within a region extending from southeastern Alaska (~130W) to the western-most Aleutian arc (~175E). Bayesloc is a probabilistic approach for earthquake location that simultaneously assesses hypocenter, phase association, travel time corrections and estimates of the precision of travel time measurements to produce a refined set of high-quality earthquake locations and associated (realistic) uncertainties. The input

datasets are a combination of local, regional and teleseismically derived location and phase information from the NEIC PDE and International Seismological Center (ISC) catalogs. A limited number of well-calibrated earthquake locations are used as a priori constraints. Results show that we can improve earthquake locations across a broad region of Alaska with systematic migration of epicenters averaging ~7 km and location errors reduced by a factor of 2. The largest shifts in location occur in the Aleutian arc.

This work represents a pilot study for a broader research project to relocate the global seismicity catalog (ISC/GEM) from 1900 to present. Our intent is to significantly improve absolute earthquake locations – in particular, within subduction zones – to: 1) improve USGS models of slab geometry (Slab 1.0 and derivatives); 2) better characterize long-term hazards of subduction zones based on improved understanding on the spatial variability of moment; and 3) significantly improve our understanding of fault kinematics from comparative studies of rupture extent (finite fault modeling) and associated aftershock distributions.

Tracking Glaciers with the Alaska Seismic Network

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More than 40 years ago it was known that calving glaciers in Alaska created unmistakable seismic signals that could be recorded tens and hundreds of kilometers away. Their long monochromatic signals invited studies that foreshadowed the more recent surge in glacier seismology. Beyond a handful of targeted studies, these signals have remained a seismic novelty. No systematic attempt has been made to catalog and track glacier seismicity across the years. Recent advances in understanding glacier sources, combined with the climate significance of tidewater glaciers, have renewed calls for comprehensive tracking of glacier seismicity in coastal Alaska. The Alaska Earthquake Center has included glacier events in its production earthquake catalog for decades. Until recently, these were best thought of as bycatch-accidental finds in the process of tracking earthquakes. Processing improvements a decade ago, combined with network improvements in the past five years, have turned this into a rich data stream capturing hundreds of events per year across 600 km of the coastal mountain range. Though the source of these signals is generally found to be iceberg calving, there are vast differences in behavior between different glacier termini. Some glaciers have strong peaks in activity during the spring, while others peak in the late summer or fall. These patterns are consistent over years pointing to fundamental differences in calving behavior. In another example, at Columbia glacier, activity began abruptly at the same time as a known change in the grounding conditions at the terminus. These observations illustrate that the current network is faithfully capturing the dynamic behavior of several glaciers in coastal Alaska. I consider, in addition, what might be possible going forward with dedicated detection schemes.

Automated Surface Wave Phase Velocity Measuring System and its Application on USArray

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Earthquake surface waves are recorded by dense seismic arrays as a strong and consistent signal among the stations. By taking advantage of the wavefield similarity of nearby stations, we have developed a new technique to estimate surface wave phase velocities precisely and automatically.

First, a time window to isolate fundamental-mode surface wave energy is built based on the group delays of all frequency bands of interest. We then calculate multi-channel broadband cross-correlation functions of the isolated waveforms from nearby stations, and fit narrow-band filtered cross correlations with a five-parameter controlled wavelet to retrieve the optimized phase difference at a range of frequencies. The amplitude of this cross-correlation function can be used to estimate the coherence, which together with signal to noise ratio (SNR) are the two key factors to exclude unqualified measurements.

The phase difference information between all the nearby station pairs for each event at each frequency is then used as the input to an Eikonal tomographic inversion for two-dimensional estimates of apparent phase velocity. We measure the amplitude of each station by adapting the same process on the auto-correlation function and perform Helmholtz tomography to estimate and remove interference (focusing and defocusing) effects. Finally, we stack the measurements of each individual event to get the final phase-velocity tomogram in each frequency band.

The entire process requires no human interaction and is highly automated. This method can be applied on data from arrays of various apertures, ranging from continental scale such as USArray, to regional scales (few hundred km) typical of PASSCAL arrays, to local-scale high-frequency arrays employed in industry and hazard investigations. By combining this analysis with programmable data acquisition services such as IRIS DMC web services, we set up an automatic system providing up-to-date surface wave phase velocity maps of USArray.

Resurrection Plate Revisited: Does a New Kinematic Model of the Yakutat, Crescent, and Siletz Terranes Solve an Old Puzzle?

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Forward kinematic modeling of Kula, Farallon (FAR), and Juan de Fuca plate motion as well as motion of the Yellowstone hotspot (YHS) relative to the Pacific (PAC) plate reconciles previously conflicting interpretations regarding the origin of Paleogene oceanic terranes currently stranded against the western North America (NAM) continental margin. By including a defunct Resurrection (RES) plate in our reconstruction of NAM, we are able to account for the Yakutat terrane in Alaska as well as the Siletz and Crescent terranes in the Pacific Northwest as remnants of a FAR-RES ridge segment that transferred to the NAM plate margin from ~53 to 42 Ma. The similarities between Yakutat and Crescent basalts [Davis & Plafker, 1986, Geology] can be explained by their having previously been adjacent parts of the RES plate. Under a simple model that the RES plate was captured by the PAC plate at the same time as the Kula plate at ~40 Ma, the distance between Yakutat and Crescent terranes may have been only a few hundred km at 50 Ma, with both formed near the YHS. Currently separated by more than 1500 km, the Yakutat terrane must have been moving northward with the PAC plate for most of the time since its formation.

Partial subduction of N. Yakutat and Crescent (RES) plate fragments and accretion of Siletz (FAR) and S. Yakutat fragments complicate the 3D structure of the Aleutian and Cascadia forearcs. The Siletz and Crescent terranes continue to move within the forearc. The Yakutat terrane includes the asperity that broke during the M9.2 1964 Alaskan earthquake, raising concerns about the seismogenic behavior of the other oceanic fragments, in particular, whether they might also act as asperities. Their rigid lower crust may also preclude aseismic strain dissipation at fault rupture ends – promoting subsequent forearc earthquakes. Our kinematic model of mobile terranes provides insights into the 3D structure of these forearcs and its relationship to ongoing seismotectonic processes.

Lithospheric Modification at the Southern Edge of Laurentia Revealed by Broadband Seismology

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The southern margin of Laurentia has been modified by a wide range of tectonic processes, including deformation due to repeated orogenies and continental collisions (Llano, Ancestral Rockies, Ouachita, Laramide) as well as ongoing rifting (at the Rio Grande Rift) and completed rifting (which created the Gulf of Mexico). Artifacts of these processes are likely to remain at lithospheric depths but, until recently, the tools needed to examine 3D structure at mantle depths beneath the region were not available. With the passage of the EarthScope's USArray and two targeted broadband deployments, new images of the region's lithosphere have emerged. These reveal lithospheric-scale anomalies that correlate strongly with surface features, such as a large fast anomaly that corresponds to the southern extent of the Laurentia (or 'Great Plains') craton and a large slow anomaly associated with the Southern Oklahoma Aulacogen. Other features were unanticipated, including slow shear velocities beneath the Texas-GoM margin, a layer that is bounded at its top and bottom by seismic discontinuities, and high levels of seismic anisotropy. Additionally a high velocity body underlying the Gulf Coast Plains may mark delaminating lower crust. If so, it provides indirect evidence that active rifting best describes the process that lead to the opening of the GoM.

Lithospheric thinning associated with the Rio Grande Rift appears to be propagating eastward and eroding the Great Plains craton. A large, seismically fast anomaly imaged beneath west Texas and southeastern New Mexico has implications for the region's structural evolution. The size, seismic velocity, and location of this anomaly suggests that it may be the result of a 'step instability,' in which progressive deformation has locally removed mantle lithosphere beneath the eastern flank of the Rio Grande Rift, resulting in thickened lithosphere at the western edge of the Great Plains craton and uplift beneath the rift flank.

Attenuation and Shear-Wave Speed Tomography in the Central US from Teleseismic Ambient Seismic Field Correlations

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Ambient seismic field correlations are nowadays widely used to get phase information of surface waves, and more recently body waves. We here focus our attention in

amplitude information contained in surface waves Green's function obtained from ambient noise correlations. We used data from a subset of USARRAY stations and a set of stations at teleseismic distances to calculate ambient noise correlation, coherence and impulse response functions. In our processing we paid particular attention in normalization of empirical Green's functions obtained from ambient noise, to minimize the effect of uneven distribution of noise sources and get reliable amplitude measurements.

Since both amplitude and phase information can be accessed using our ambient noise correlations, we perform velocity and attenuation tomography in the central US. Both attenuation and S-wave velocity maps show a strong correlation with the geological features in the study region, and quantitative analysis of Vs and Qs allows for better constraining the thermal and tectonic structures within the lithosphere. Our results pave the way of a systematical study of crust and upper mantle attenuation using ambient noise, avoiding the need to wait for earthquakes.

Monitoring Dynamic Changes at Active Volcanoes and Fault Zones

Oral Session · Thursday · 8:30 AM · 1 May · Room 7/8 Session
Chairs: Ninfa Bennington, Matt Haney and Silvio de Angelis

Detecting Temporal Changes in Active Fault Zones During Large Earthquake Cycles

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Large earthquakes change not only nearby seismicity patterns, but also seismic properties of surrounding medium. An improved understanding of temporal evolution of fault zone (FZ) properties during earthquake cycles has important implications for many aspects of earthquake physics, including long-term evolutions of FZ structures, interactions of earthquakes and faults, and seismic hazard mitigation.

Recent studies based on waveform cross-correlations of repeating earthquakes have found small but resolvable changes of seismic velocities in shallow surface layers and around active fault zones associated with the occurrences of major earthquakes or aseismic slip events. However, repeating earthquakes only occurred in certain locations and we could not control their occurrence times, resulting in inadequate temporal sampling. Another emerging tool to measure temporal changes is via auto- and cross-correlations of ambient seismic wavefields, also known as passive imaging or seismic interferometry. Because ambient wavefields exist all the time in many regions and are relatively stable, they provide an ideal source for continuous monitoring of the temporal changes of FZ properties.

In this presentation I briefly review recent developments in measuring temporal changes using repeating earthquakes and ambient noises. I will also present new results on detecting temporal changes of fault zone properties around the epicentral regions of the 2008 Mw7.9 Wenchuan earthquake and the 2012 Mw7.6 Costa Rica earthquake. The obtained results will be compared with seismicity patterns, mainshock slip distribution and pre- and post-seismic deformation to determine the physical mechanisms responsible for causing the observed temporal changes in seismic velocities.

Imaging Dynamic Changes in Heterogeneous Structures using Diffuse Waves: From Theory to Applications

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Direct waves traveling through heterogeneous structures are strongly attenuated. Classical imaging techniques, based on the arrival time of such waves are then difficult or impossible to apply. This limitation holds at different scales, from ultrasound propagating through concrete to seismic waves propagating through volcanoes or fault zones, these media being strongly heterogeneous at the wavelength scale.

The energy of the direct wave is not lost though, but distributed to multiply scattered waves, also called coda waves. Due to the complexity of their apparently random trajectories, these coda waves have long been considered as devoid of any useful information. But thanks to their longer trajectories, coda waves also show great sensitivity to small changes occurring in the medium. Based on this feature, the doublet or the stretching technique have been widely used to measure small velocity changes on volcanoes, fault zones, reservoirs. . .

However, if these techniques give a spatial average of the changes occurring in the medium, they do not provide any information on their positions. Interestingly, the variation of the coda waveform depends on the position of the change relative to the sensors. The phase-shift in coda waves induced by a small and local velocity change is related to a diffuse sensitivity kernel. We showed that when a strong change, or structural change, occurs in the medium, the waveform variation is not a phase-shift but a distortion. This decorrelation is predicted by an expression based on the same sensitivity kernel.

Going one step further, we used this sensitivity kernel to solve an inverse problem that allows to image local changes taking place in heterogeneous structures. From theory to applications in volcanoes and fault zone monitoring, through numerical simulations and laboratory experiments, we give a review of the different efforts engaged around this method and the encouraging first results that we obtained.

Nonlinear Site Response in Medium Magnitude Earthquakes Near Parkfield, California

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Careful analysis of strong-motion recordings of 13 medium magnitude earthquakes ($3.7 \leq M \leq 6.5$) in the Parkfield, California, area shows that very modest levels of shaking (approximately 3.5% of the acceleration of gravity) can produce observable changes in site response. Specifically, I observe a drop and subsequent recovery of the resonant frequency at sites that are part of the USGS Parkfield dense seismograph array (UPSAR) and Turkey Flat array. While further work is necessary to fully eliminate other models, given that these frequency shifts correlate with the strength of shaking at the Turkey Flat array and only appear for the strongest shaking levels at UPSAR, the most plausible explanation for them is that they are a result of nonlinear site response. Assuming this to be true, the observation of nonlinear site response in small ($M < 5$) earthquakes implies that nonlinear site response can occur at much lower levels of shaking than previously believed. I present observations of a resonant frequency shift during five $M \leq 5$ earthquakes near Parkfield, California, strongly contrasting with previous studies that have only identified non- linear site effects for much larger events. In addition to the nonlinear effects seen for the smaller events, nonlinear site response is also observed for two largest earthquakes in the region during the study period (the 2003 M 6.5 San Simeon earthquake and the 2004 M 6 Parkfield earthquake).

4D Reflection Monitoring of Deep Magma: Lessons from the SEA-CALIPSO Experiment

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Although reflection profiling in surficial volcanic terrain has been problematic in resource exploration, deep reflection profiles in many parts of the world have detected strong returns from what is often interpreted as molten material at middle and lower crustal depths. This suggests that repeated deep surveys have the potential for detecting relatively small changes in magma position and properties with time. The potential for 4D reflection monitoring of the roots of an active andesitic volcanic system was one consideration in the design and execution of the SEA-CALIPSO onshore-offshore seismic experiment in 2007 on Montserrat in the Caribbean SEA-CALIPSO consisted of an extensive deployment of seismographs on land and the ocean bottom to record an airgun shots on a series of circular and radial lines around the island. Here we will review the modeling used to guide the design of the reflection component of this experiment, the actual logistical constraints which compromised those designs, and the potential of using natural sources instead of airguns to achieve a more favorable target illumination. In particular, we will show recent analyses that suggest that seismic interferometry might be used to improve deep reflection imaging of tectonically active where physical access is limited for both sources and receivers. In particular, body waves recovered from seismic interferometric analysis of dense array recordings offer the potential for continuous monitoring of temporal changes at depth which greatly improve on the resolution offered by similar analyses of surface wave.

Three-Dimensional Velocity Structure of the Galeras Volcano (Colombia) from Local Earthquake Tomography and Evolution of the Volcanic Activity

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An estimation of the three-dimensional Vp structure of the Galeras volcano was done up to ~8 km depth relative to the top. Using a passive local seismic tomography

with 7668 P-wave first arrivals associated to 1183 volcano- tectonic earthquakes (1989–2009) and recorded by the seismic network of the Volcanological and Seismological Observatory of Pasto. The seismic events may correspond to fractures on the solid rock in response to pressure – induced movement of magma and volcanic fluids. Two zones of lower velocity and two zones with high of velocity are essentially defined. The low velocity anomalies are located at the SE and the WNW from the volcanic summit and could be associated with geothermal anomalous regions where there is not fragility enough for generating fractures. Superficial nature of these zones suggest that they could obey to remnants of a hydrothermal systems with not solidified magma. Under the active crater of the Galeras volcano, is highlighted with anomalies of high velocity, a vertical like-pipe structure up to about 4 km depth with a strongly clustered and aligned seismic activity. We hypothesize that this structure corresponds to a duct system whose fractures are the way for ascending magma from deeper levels (>8 km) to the top. Towards the NE from the active crater and below the surface (4–6 km depth), the intersection of the Silvia-Pijao and Buesaco faults, matches with high velocity anomalies (~4.5 km/s). These velocities, which are concordant with measurements of andesitic magmas solidified or rigid bodies of metamorphic rocks, correspond to a region where it is also observed a concentration of energetic volcano-tectonic events. In general, the volcanic structure consists of low velocity materials that correlate with young and unconsolidated deposits, as well as old and highly fractured or altered volcanic materials. Attenuation anomalies and temporal evolution of the volcanic activity is also explained in light of these results.

Changes in Seismic Velocity During the 2004–2008 Eruption of Mount St. Helens Volcano

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Mount St. Helens (MSH) effusively erupted in late 2004, following an 18-year quiescence. Many swarms of repeating earthquakes accompanied the extrusion and in some cases the waveforms from these earthquakes evolved slowly, possibly reflecting changes in the properties of the volcano that affect seismic wave propagation. We use coda-wave interferometry to quantify these changes in terms of small (usually <1%) changes in seismic velocity structure by determining how relatively condensed or stretched the coda is between two similar earthquakes. We then utilize several hundred distinct families of repeating earthquakes at once to create a continuous function of velocity change observed at any station in the seismic network. The high rate of earthquakes allows us to track these changes on a daily or even hourly time scale. Following years of no seismic velocity changes larger than those due to climatic processes (tenths of a percent), we observed decreases in seismic velocity of >1% coincident with the onset of increased earthquake activity beginning September 23, 2004. These changes are largest near the dome of the volcano, and likely related to shallow deformation as magma first worked its way to the surface. Changes in velocity are often attributed to deformation, especially volumetric strain and the opening or closing of cracks, but also with nonlinear responses to ground shaking and fluid intrusion or saturation. We find strong correlation between velocity changes and real-time seismic amplitude (RSAM) during the first three weeks of activity, suggesting fluctuations of pressure in the shallow subsurface may have driven both seismicity and velocity change.

Observations of Time-Lapsed Velocity Changes at Yellowstone from Ambient Noise Correlation Functions

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In geologically active regions, the time lag of the ambient Noise Correlation Function (NCF) can change or migrate, according to changes in the subsurface velocity structure. This is currently being observed in many volcanic settings around the world, most notably at the Piton de la Fournaise shield volcano on Réunion Island. Typically these velocity changes occur very abruptly, signifying an obvious change associated with inflation of the magma chamber in a pre-eruptive phase. In this work, however, we examine much longer-term trends at Yellowstone, where there isn't an obvious event, but there is a geodetically observed uplift that occurred from 2004–2010. In doing so, we must also correct for, and remove, apparent velocity changes due to seasonal variations in the ambient seismic field as well. We examine the time-lagged differences of the direct arrival of the NCF, rather than the coda, by drastically improving the signal-to-noise ratio of the NCF through the development of the adaptive covariance filter (ACF). By utilizing velocity variations in these main arrivals, it becomes more straightforward to spatially locate these changes and understand their temporal resolution. We use all available data near the Yellowstone caldera, including permanent and temporary networks such as the USArray and NOISY projects, to spatially locate and observe decreased velocities at surface wave periods consistent with depths of the magma chamber beneath Yellowstone. We will then use this information to eventually create time-lapsed tomographic images of Yellowstone.

Dynamics of the Yellowstone Volcanic System Using 4-D Seismic Imaging

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It is well established that there is a body of partial melt driving the Yellowstone volcanic system at upper crustal depths. The magma reservoir underlies the 0.64 Ma Yellowstone caldera at depths of 5–15 km and extends 17 km northeast of the caldera at depths less than 5 km. A recent study showed that the Yellowstone magma reservoir is 2.5 times larger than previously thought. Local earthquake tomography techniques have been used to image the Yellowstone magma reservoir using the Yellowstone Seismic Network and earthquakes from 1973 to the present. In addition, leveling, GPS, and InSAR measurements have tracked the inflation and deflation cycles of the Yellowstone volcanic system from 1923 to the present. Results show decadal scales of uplift and subsidence, mainly contained in the 0.64 Ma caldera, with rates of uplift up to 7 cm/yr that have been attributed to cycles of magma recharge in the magma reservoir. Here we investigate the time-dependent velocity structure of the Yellowstone volcanic system by examining the seismic velocity structure for various time periods that correspond to main historic uplift and subsidence episodes in Yellowstone. We will also examine the crustal structure at time periods that have large earthquake swarms that may have contributed to the migration of magmatic fluids including the 1985 western caldera swarm, the 2008–2009 Yellowstone Lake swarm, and the 2010 Madison Plateau swarm.

Monitoring Changes in Seismic Velocity Related to Magmatism at Okmok and Redoubt Volcanoes, Alaska

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Okmok and Redoubt are two of the most active volcanoes in the Aleutian Arc. Leading up to its most recent eruption, Okmok, a shield volcano on Umnak Island, showed precursors to volcanic activity only five hours before it erupted explosively in July 2008. Currently, permanent GPS instruments at Okmok volcano show rapid uplift occurring within its caldera. Redoubt, a stratovolcano located along the Cook Inlet, displayed several months of precursory activity leading up to its March 2009 eruption. Frequent activity at both volcanoes poses a major hazard to the North Pacific air routes. Also, Okmok is adjacent to some of the world's most productive fisheries and Redoubt is located near Anchorage, the major population center of Alaska. For these reasons, it is imperative that we improve our ability to detect early signs of volcanic unrest.

We take advantage of continuous waveforms recorded on seismic networks at Redoubt and Okmok in an attempt to identify seismic precursors related to volcanic activity. Seismic interferometry using ambient noise is performed in order to probe the subsurface and determine temporal changes in relative seismic velocity. For the current period of rapid uplift at Okmok, our investigation shows a continual decrease in seismic velocity over a 4 month time period starting in August 2013 for station pairs with paths traversing the caldera. The cumulative decrease in seismic velocity is largest for the station pair within the caldera (~0.5% decrease) and near to the 2008 eruption vents. Station pairs outside Okmok's caldera show no change in seismic velocity. This suggests that inflation is constrained to the caldera and occurring near the 2008 eruption site. Since GPS instruments indicate ongoing uplift at Okmok, future work will include analysis of noise cross-correlation data into present day. Additional future work will focus on identifying temporal changes in seismic velocity related to the 2008 Okmok and 2009 Redoubt volcanic eruptions.

Imaging Seismic Source Variations with Back-Projection Methods at Sierra Negra Volcano, Galápagos Islands

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Seismic records from volcanic systems are typically 'noisy,' making it difficult to pick unique seismic wave arrivals and resolve 3D subsurface structures with traditional seismic imaging methods. Similarly, seismic signals generated by

ongoing volcanic processes in the subsurface (volcanic tremor) tend to be very low-magnitude and difficult to observe remotely. High-amplitude bursts within the 'noise' (eruptions) occur infrequently relative to the duration of an eruption cycle and shed minimal insight into the mechanisms that occur leading up to and recovering from eruptions; however, the abundant 'noise' observed on volcanic seismic records represents a series of overlapping low-magnitude displacements directly linked to magma, fluid and volatile movement at depth. Volcanic 'noise' therefore likely contains information about subsurface processes that occur in a volcanic system before, during, and after an eruption.

This study presents a new method to comprehensively study variations in repeated 'micro-events' recorded at Sierra Negra Volcano during a proposed dike intrusion in June 2010. We apply a back-projection search algorithm to analyze coherent seismic energy from all possible subsurface source locations to all available receiver-pairs. Through stacking, the method finds the most likely subsurface locations generating repeating, low-magnitude seismic signals over the stack-interval (i.e. 1-hr). Initial results were found using normalized, bandpass filtered vertical records broken into 10-sec non-overlapping time-windows, correlated and stacked over 1-hr using a single P-wave moveout velocity of 5.8 km/s. These results agree well with previously determined micro-event locations associated with the proposed intrusion. Additional pre-processing and filtering in the application of the method now allows us to analyze specific volcanic tremor frequency bands (1–10 Hz) and seismic phases (P, SV, SH) to better understand the nature of the imaged seismic sources.

Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications

Oral Session · Thursday · 1:30 PM · 1 May · Room 7/8 Session Chairs: Sanaz Rezaeian, Christine Goulet, John Anderson and Mark Petersen

The 2014 Update of the United States National Seismic Hazard Models

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During the past three years, the USGS updated the U.S. National Seismic Hazard models for the lower 48 states. These products are considered for inclusion in future building codes, risk assessments, and public policy applications. The seismic hazard models are based on our assessment of the best available science at the time of the update, and incorporate a broad range of models and parameters. Several new datasets and models have been developed since the 2008 update. For the Central and Eastern U.S. we implemented a new moment magnitude (Mw) catalog and completeness estimates, updated the maximum magnitude distribution, updated and tested the smoothing algorithms for adaptive and fixed-radius methods for estimating earthquake rates away from faults, modified the sizes and rates of New Madrid Seismic Zone earthquakes, and considered induced earthquakes. In the Intermountain West we implemented new smoothing algorithms, fault geometries for normal faults, multiple Wasatch fault alternatives, and fault slip rates based on models obtained by inverting geodetic and geologic data together. For the Pacific NW we developed new Cascadia fault rupture models that incorporate additional earthquakes in the south, added the Tacoma fault and an eastern extension of the Whidbey Island fault, and implemented the new geodetic-geologic based slip rates. For California we implemented the new UCERF3 source model that allows for a more complete inventory of fault ruptures and is based on new deformation models, magnitude-area equations, and seismicity input parameters. We also applied several new published ground motion models for shallow crustal earthquakes, subduction interface, and deep earthquakes. The many improvements in input models resulted in small changes across most of the country, but have caused significant changes up to ±25% at 1 Hz and 5 Hz spectral accelerations in localized places. Hazard information is available on-line: http://earthquake.usgs.gov/hazmaps/.

Recommendations for Future Updates of the National Seismic Hazard Maps

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In May and August 2013, the authors met to provide a late-stage peer review of the 2014 U.S. Geological Survey (USGS) National Seismic Hazard Map (NSHM). Subsequently, the USGS leadership recommended that our committee, designated the National Steering Committee for National Seismic Hazard and Risk Assessment, should become a standing sub-committee of the Scientific Earthquake Studies Advisory Committee to provide independent, comprehensive input to the hazard mapping process.

The Committee concluded that the 2014 NSHM uses appropriate data, models, and methods for input, and is appropriate for application in building codes, risk assessments, and other purposes for which the maps are generally used. In addition to short term recommendations, we made several recommendations for future updates. The quality of the National Seismic Hazard Map depends on the quality of the source characterization model and the ground motion characterization model (e.g., ground motion prediction equations, GMPEs), both of which are strongly data driven. Ongoing observations and research in every part of the US are essential to better constrain source models (including Mmax) and GMPEs. Induced seismicity capable of causing damage introduces challenges that require both research and policy development because the characteristics of induced seismicity distinguish it from background seismic activity. We suggested that USGS use some type of overlay to the 2014 maps to independently represent the time- and space-dependent hazards associated with induced earthquakes. Other future issues include time-dependent source models, the ergodic assumption, use of geodesy to constrain source models, improved scaling relations and handling of all uncertainties.

The Committee supports the USGS policy of basing the map input on peer-reviewed studies. To allow adequate time for these studies to be carefully implemented, we recommend that USGS set a cutoff date for new materials to be included in future maps

The 2014 National Seisimic Hazard Maps: Updated Catalogs and Seismicity Models

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The U. S. Geological Survey (USGS) has developed new earthquake catalogs and seismicity-based source models for the 2014 National Seismic Hazard Maps. The greatest changes from 2008 occur in the central and eastern U. S. (CEUS), where we transition from body-wave-magnitude-based catalogs and models to moment magnitude. Some elements are adapted from a large hazard study completed in 2012 by the CEUS-SSC Project (www.ceus-ssc.com). We develop a uniform catalog through 2012 from several source catalogs, using CEUS-SSC magnitude conversions and magnitude uncertainty adjustments. As before, non-tectonic earthquakes are deleted from the declustered catalog for the building code maps. For 2014, however, development of a consensus approach for suspected fluid-induced seismicity is more complex and controversial, due to the new locations, high rates, and large magnitudes of some recent activity. Alternative maps are under development to account for the hazard from these earthquakes. The three CEUS seismicity-rate 'agrid' models are updated, with new catalog statistics, a b value of 1.0, and magnitude cutoff levels adjusted from body-wave magnitude 3, 4, 5 to moment magnitude 2.7, 3.7, 4.7. A new seven-zone completeness model is developed to account for historical demographic and instrumentation trends. Maximum-magnitude ranges are broadened, and an alternative maximum-magnitude zonation is adapted from CEUS-SSC and combined with the 2008 zonation in a logic tree. The new western U. S. (WUS) catalogs and seismicity source models are fairly straightforward updates from 2008. We update the WUS moment-magnitude catalog through 2012. UCERF3 results (USGS Open-File Report 2013–1165) are used for California. For both CEUS and WUS agrids, a new nearest-neighbor smoothing algorithm is implemented and combined with the 2008 fixed-distance model in a logic tree.

Ground Motion Models Used in the 2014 U.S. National Seismic Hazard Maps

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The 2014 update of the U.S. National Seismic Hazard Maps (NSHMs) includes modifications to the seismic source models and the ground motion models (GMMs) applied to sites across the conterminous U.S. This presentation focuses on modifications to GMMs relative to the 2008 update of the NSHMs. In the Central and Eastern U.S. (CEUS), three of the eight ground motion models used are new or have been modified since the previous version of the NSHMs. But the main changes are due to the modified weights applied in the construction of the mean ground motion. Relative model weightings are assigned by grouping the GMMs by model type (e.g., waveform model, hybrid model, etc.) and geometric spreading terms. Compared to the 2008 NSHMs, larger weights are applied to GMMs employing geometric spreading models that decay faster. As a result, the new GMMs and updated weights tend to decrease the probabilistic ground motions in the 2014 NSHMs relative to the 2008 NSHMs by 10–20% across most of the CEUS. In the Western United States (WUS), five new GMMs developed by the Next Generation Attenuation (NGA-West2) project are used for shallow crustal earthquakes in active tectonic regions. Previous versions of three GMMs from the NGA-West1 project were used in 2008. In general, the combined effects of lower medians and higher standard deviations in the updated GMMs cause only small changes, within 5–20%, in the probabilistic ground motions across the WUS relative to the 2008 NSHMs. In the Pacific Northwest region (PNW), updated GMMs for interface and intraslab earthquakes are included. One outdated GMM has been removed and ground motions are now characterized with four GMMs as opposed to the three GMMs used in 2008 for both interface and intraslab earthquakes. Interface near-source probabilistic ground motions are now higher; however, ground motions attenuate more rapidly with distance in the 2014 NSHMs. Overall changes due to update of GMMs in the PNW are less than 5–10%.

New Time-Independent and Time-Dependent Seismic Source Models for the Wasatch Front, Utah for the National Seismic Hazard Maps

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The Working Group on Utah Earthquake Probabilities (WGUEP) has developed new time-independent and time-dependent seismic source models for the Wasatch Front region, Utah. The WGUEP's goal is to develop a probabilistic earthquake forecast for the region that includes (1) a time-dependent earthquake forecast (M 6.75 and greater) for the five central segments of the Wasatch fault and two segments of the Great Salt Lake fault, (2) time-independent forecasts for other less well studied faults, and (3) an estimate of the time-independent probability of earthquakes in the M 5 and greater range to account for potentially damaging background earthquakes. Logic trees were developed to address epistemic uncertainties in the model components. GPS data were used to check the regional seismic moment rate of the time-independent model but not to estimate fault slip rates. The WGUEP has rigorously evaluated and updated surface-faulting earthquake chronologies and recurrence-interval estimates for the five central segments of the Wasatch fault. Revised segment-wide earthquake chronologies and fault displacements provide the basis for six fault rupture models including (1) single segment ruptures only, (2) combinations of single- and multi-segment ruptures, and (3) an unsegmented (floating earthquake) scenario. The time-independent model has been incorporated into the 2014 National Seismic Hazard Maps (NSHMs) by the U.S. Geological Survey (USGS). Although the Wasatch Front time-dependent model was not used by the USGS, it is strongly favored by the WGUEP based on fault rupture behavior patterns. Differences in the time-dependent and time-independent hazard can be significant along the central segments of the Wasatch fault because of the long elapsed times since the last large surface-faulting earthquake on some segments. We envision that incorporating time-dependent models will be the next step in improving the NSHMs.

Integrating UCERF3 into the 2014 National Seismic Hazard Maps

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The California component of the 2014 National Seismic Hazard Map (NSHM) is based on the third version of the Uniform California Earthquake Rupture Forecast (UCERF3) and marks a significant departure from prior California earthquake rate models. UCERF3 is a product of the Working Group on California Earthquake Probabilities (WGCEP), whose goal was to develop a model that relaxes assumptions of fault-segmentation and includes multi-fault ruptures. To accomplish this, UCERF3 leverages a newly developed 'grand inversion' platform, which solves for the rate of all California earthquakes simultaneously using a broad range of data constraints (e.g. fault-slip rates, paleoseismic event rates, and regional and fault-specific magnitude frequency distributions, etc.). This approach eliminates the apparent UCERF2 over-prediction of M6.5–7 earthquake rates and permits inclusion of multi-fault ruptures similar to those recently observed (e.g. the 2002 MW 7.9 Denali, Alaska earthquake). The broad range of epistemic uncertainties spanned by UCERF3 poses some difficulty when trying to understand how the model will impact seismic hazard. In advance of UCERF3's release, we made considerable effort to identify and explain the largest changes in seismic hazard. These exercises were conducted using the next generation attenuation relationships for the western US (NGA-West1) used in the 2008 NSHM.

We present an overview of UCERF3 and its effect on the 2014 NSHM. The release of updated ground motion models (NGA-West2) for use in the 2014 NSHM gives rise to additional changes in hazard because the new models are more sensitive to certain styles of faulting and the large magnitude events present in UCERF3. We also explore issues associated with integrating the model with the rest of the NSHM in the western US so as to avoid double counting of sources. Lastly we discuss a strategy for public release of the model via USGS channels that is compatible with the NSHM outside of California.

A Summary of Findings and Models of the NGA-West2 Research Program

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The NGA-West2 project is a large multidisciplinary, multi-year research program on the Next Generation Attenuation models for shallow crustal earthquakes in active tectonic regions. The research project has been coordinated by the Pacific Earthquake Engineering Research Center (PEER) with extensive technical interactions among many individuals and organizations. NGA-West2 addresses several key issues in ground-motion seismic hazard including: updating the NGA database for a magnitude range of 3.0–7.9; updating NGA ground-motion prediction equations (GMPEs) for the 'average' horizontal component; scaling response spectra for damping values other than 5%; quantifying the effects of directivity and directionality for horizontal ground motion; resolving discrepancies between the NGA and the National Earthquake Hazards Reduction Program (NEHRP) site amplification factors; analysis of epistemic uncertainty for NGA GMPEs; and developing GMPEs for vertical ground motion. A summary of findings and models of the NGA-West2 project is presented.

Proposed Earthquake Ground Motion Maps for Model Building Codes based on the 2014 United States Geological Survey National Seismic Hazard Model

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The 2014 National Seismic Hazard Model (NSHM) for the conterminous United States developed by the United States Geological Survey (USGS) is the earth-science basis for a proposal to update derivative earthquake ground motion maps for the *2015 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. If accepted, the updated maps would likely be adopted for the *2018 International Building Code* (*IBC*), just as Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motion maps based on the 2008 NSHM were adopted for the *2012 IBC*. As established by the Building Seismic Safety Council Provisions Update Committee, with funding from the Federal Emergency Management Agency, the MCE_R ground motion maps are derived from the USGS NSHMs in two steps. First, the computed USGS hazard curves (of annual frequency of exceedance vs. ground motion spectral acceleration) are used to calculate 'risk-targeted' ground motions that, when used in designing new buildings, are anticipated to result in a geographically uniform annual frequency of collapse (or 'risk of collapse'). In doing so, well-established regional (e.g., western vs. central and eastern US) differences in shapes of the hazard curves are captured. Second, the USGS NSHM is also used to

compute corresponding deterministic ground motions that are applied as caps to the probabilistic risk-targeted ground motions, mainly near major faults in California. The procedure for computing these deterministic ground motions, as well as that for calculating the probabilistic risk-targeted ground motions, is stipulated in the site-specific hazard analysis portion of the *NEHRP Provisions*. In this presentation, we elaborate on the derivation of MCE_R ground motions from the NSHM, and illustrate the impacts of the NSHM updates on seismic design of new buildings and other structures at 34 high-risk (i.e., high-hazard and/or large-population) city locations.

On NGA and NEHRP Site Coefficients Inferred for Site Classes in US Building Codes

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Site coefficients, derived herein from Next Generation Ground Motion Prediction Equations (NGA GMPEs), agree well with NEHRP site coefficients at low levels of input motion (0.1g) and those observed from the Loma Prieta earthquake. For higher levels of input motion, the majority of the NEHRP values are within the 95 % epistemic-uncertainty limits implied by the NGA estimates with the exceptions being the mid-period site coefficient, Fv for site class D and the short-period coefficient, Fa for site class C, both of which are slightly less than the corresponding 95% limit. Proposals by the author to adjust the NEHRP coefficients to the mean of the NGA site coefficients inferred with respect to Vs30 midpoint for reference site class B yield site coefficients consistent with the definitions of the simplified site classes adopted in US building codes. The proposed mean NGA coefficients 1) yield unity amplification independent of ground motion level for the reference site class B, 2) are consistent with those used for the adopted Maximum Considered Earthquake Response maps (MCER), 3) account for the epistemic uncertainty implied by the four NGA GMPE models, and 4) are consistent with average surface spectral amplifications observed in past earthquakes with average Vs30 $\sim$ 800 m/s and 5) can be easily updated with future improvements in NGA GMPEs. The NGA data base implies that the median Vs30 value for site class B (Vs30 $\sim$ 900 m/s) is more typical than 760 m/s as a value to characterize firm to hard rock sites as a possible less conservative reference for future MCER maps.

Preliminary Application of the 2014 U.S. National Seismic Hazard Map and its Implication in the Reinsurance Industry

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Using GIS techniques, a draft release of the 2% in 50-year 2014 U.S. National Seismic Hazard Map for 1-second spectral acceleration was manipulated and applied to Validus Research's current catastrophe modelling framework for the United States. The hazard change was implemented as either a frequency or severity adjustment to study the range of possible loss impacts to an industry exposure database (IED) for the United States and to key anonymous insurers with exposures in California and New Madrid in the reinsurance industry. Using an IED, results show an overall increase in losses for the whole United States. Although such is the case, the Northeast and New Madrid regions show a decrease in losses, meaning that the increased losses in the rest of the United States is the key driver for change. The impact results on key anonymous insurers confirm that of the IED in that losses increase for California-exposure-based insurance companies and losses decrease for New Madrid-exposure-based insurance companies.

Joyner Lecture

Oral Session · Thursday · 5.15 PM · 1 May · Hilton

Ground-motion prediction equations: Past, present, and future

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Ground-motion prediction equations (GMPEs) typically give amplitudes of ground motion as a function of distance from earthquakes of a particular magnitude. They are the foundations on which the seismic hazard maps used in building codes are built, they provide motions for the design of critical structures, and they and the databases used in their derivation conveniently summarize a large amount of information about the seismic waves radiated from earthquakes. The development of GMPEs requires knowledge of many aspects of seismology, including data acquisition, data processing, source physics, the determination of crustal structure, the effects of that structure on the propagation of seismic waves, the measurement and characterization of the geotechnical properties near the Earth's surface, and the nonlinear response of soils to strong shaking. Generally, GMPEs are developed for three regions: active crustal regions (ACR), stable continental regions (SCR), and subduction zones (SZ). Most GMPEs in ACRs and SZs are based on empirical analysis of observed ground motion, while those in data-poor areas such as SCRs rely primarily on simulations of ground shaking. As data sets increase and theoretical simulations improve, previous GMPEs are revised and new ones are proposed. As a result, many hundreds of GMPEs have been published, and more are on their way. As an example of the current state-of-practice for GMPEs in ACRs, I will discuss a recent multi-year project undertaken by the Pacific Earthquake Engineering Research Center (PEER). The future is bound to bring more data, but most of these data will be for magnitudes and distances where present GMPEs are well constrained by existing data, at least in ACRs. Significant gaps will continue to exist in our knowledge of ground shaking in certain distance and magnitude ranges for ACRs and for SCRs in general. For this reason, combinations of simulated and observed motions will be used to create future GMPEs.

Alaska Update of the USGS National Seismic Hazard Maps

Poster Session · Thursday · 1 May · Cook/Arteaga

Earthquake Risk in Alaska

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In anticipation of the upcoming update of the Alaska seismic hazard map by the USGS we investigate the possible impact of hazard changes on seismic risk. First order standard components that build up a probabilistic seismic risk model are hazard, building response, and a financial loss model. The hazard component in the current RMS Alaska earthquake risk model is based on the 2007 probabilistic seismic hazard maps for Alaska (Wesson et al., 2007; Boyd et al., 2007). Statewide risk based on the 2007 hazard maps is controlled by the subduction zone mega-thrust earthquakes. We implement newly gained insights into generation (segmentation), maximum magnitude and impact (ground motions) of mega-thrust earthquakes and their time-dependent behavior. We expand the event set with earthquakes representing multiple-fault ruptures (following a modified UCERF3 approach). Instead of modeling the intraslab earthquakes at a uniform depth we implement these deep events in a step-wise manner, similarly to what is proposed for Cascadia by NSHMP, thus producing shallower events closer to the trench and deeper events under the mainland. We identify areas of potential extreme liquefaction and landslide. The resulting seismic risk model has a less uniform source distribution, with larger contributions from crustal fault and intraslab sources. Considered risk metrics include simple scenario calculations, where we model regional damage and loss due to one earthquake, average annual loss, an annualized expected loss level used by insurers to set their annual premium rates, and the loss exceedance probability curve used by insurers to address their solvency and manage their portfolio risk. We analyze risk profile changes in areas with large population density and for structures of economic and financial importance: the Trans-Alaska pipeline, industrial facilities in Valdez and typical residential wood buildings in Anchorage, Fairbanks and Juneau

Preliminary Results from the Watana Seismic Network and Development of a 3D Slab Model, South-Central Alaska

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In August 2012 the Alaska Earthquake Center (AEC) installed four seismograph stations in the vicinity of the proposed Watana Dam site in south-central Alaska, with three stations added in the summer of 2013. Instrumentation consists of 3-component broadband sensors, with strong motion instruments at 4 of the sites. This sub-network is integrated into the AEC regional network, with waveforms sent to IRIS DMC. Station spacing is on the order of 10–20 km, and covers a part of Alaska that had previously been poorly monitored. Magnitude completeness appears to be 1.0 or lower, in a region roughly 75 km EW and 50 km NS. The

network is above the northwest-dipping Pacific plate, which lies at depths of 40 to 100 km beneath the network area, and dips at an angle of 20–25 degrees The largest slab and crustal events recorded with the newly installed network have magnitudes of 4.0 and 3.8, respectively. 3–4 clusters or mainshock-aftershock sequences have been observed in the crustal seismicity. A total of 1070 events (432 in the crust, 638 in the slab) have been located between network initiation and the end of 2013, for an average rate of about four earthquakes per day. Results from the network, in addition to AEC data from July 1988 onward, were used to develop a 3D slab model for central Alaska. Using 3D visualization software, a total of 7 slab segments were identified, ranging in depths from 40 to 300 km, whose strikes and dips were determined by least-squares fits to the hypocentral data. The resulting source model was applied by projecting Gaussian-smoothed seismicity onto the identified planes, resulting in more accurate distance determinations to specific sites. For sites lying about 60 km above the down-going slab results are similar to those in Wesson et al. (2007) (since they used a single depth of 60 km to model upper slab seismicity) but are likely to be different for sites lying closer to or farther away from the slab.

Slip on the Suckling Hills Splay Fault during the 1964 Alaska Earthquake

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The Suckling Hills in southern Alaska experienced localized, anomalously high coseismic uplift in the Mw 9.2, 1964 Alaska earthquake. High uplift at the Suckling Hills can be explained by increased slip, or an asperity, on the Aleutian megathrust, however, new research suggests that increased uplift may be a result of slip on the recently mapped Suckling Hills splay fault. We present a series of models that demonstrate how the inclusion of the Suckling Hills fault improves the fit between modeled vertical displacement and measured coseismic uplift in comparison to slip on the Aleutian megathrust alone. Our results suggest ~3m of slip in the 1964 earthquake on the Suckling Hills fault to explain the high coseismic uplift data. These results are consistent with recent studies indicating Pleistocene slip on the Suckling Hills fault and together highlight the potential seismic and tsunami risk associated with this segment of the Alaskan subduction complex.

Creation of the Alaska Earthquake Scenario Atlas: Using ShakeMap to Improve Awareness of Seismic Hazard and Risk in the Last Frontier

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Large and damaging earthquakes are a threat to populations in all areas of Alaska. To help plan for the inevitable, the Alaska Earthquake Center (AEC) is creating an updated Earthquake Scenario Atlas as part of the revised National Seismic Hazard Map in Alaska. The Atlas contains ShakeMaps from a number of theoretical and historical earthquakes in the state, including the 1964 M9.2 Good Friday earthquake. ShakeMap is a well-regarded system created by the U.S. Geological Survey (USGS) to produce maps of measured and predicted ground-motions for real and scenario earthquakes; many seismic networks throughout the world use it operationally. The AEC uses ShakeMap on a daily basis to serve information about recent earthquakes to stakeholders and the general public. In addition, customized ShakeMaps are produced for notable earthquakes near the Trans-Alaska Pipeline and made available to Alyeska, the pipeline operator. These ShakeMaps are part of a larger system designed to alert Alyeska of any strong motions that could cause damage to the pipeline infrastructure to help minimize economic and environmental issues. However, the need to evaluate hazards from future earthquakes led AEC to produce a suite of scenario ShakeMaps culled from the large catalog of historic earthquakes as well as fault segments used in the 2007 USGS hazard map. Many of these scenario earthquakes occurred before the creation of a true seismic network in Alaska, limiting the data products that have been available for these earthquakes. Additionally, logistical challenges in remote areas of the state limit our knowledge of the local geology in many places. The Earthquake Scenario Atlas thus provides communities and state and federal agencies access to ground shaking estimates. Visual representations of these data have tremendous outreach value as a stand-alone product. In addition, the Atlas provides spatial data that are the building blocks for hazard analyses and loss modeling.

Estimating Mmax of Intraslab Earthquakes

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A study was performed to estimate the maximum magnitude (Mmax) of global intraslab earthquakes. The global subduction zone regions delineated by Hayes et al. (2012) were used in this study with the addition of the Caribbean subduction zone. Seismicity data (M7+) obtained from the International Seismological Center (ISC) Bulletin and the EHB Bulletin were collected for each of these regions. Magnitude vs. depth plots were created for each region in order to visualize the magnitude and depth ranges occurring in each region and to identify the intraslab events (considered to be deeper than 100 km). A bimodal pattern appears to be present as the Mmax decreases from 100 to 400 km in depth but between 400 and 700 km in depth Mmax increases again. Mmax in the different regions varied between 7.3 to 8.3, with larger Mmaxes associated with the deeper (400 to 700 km) range. Frohlich (1998, 2006) noted a possible Mmax dependence on chemical, thermal, and mechanical changes in the slab with increasing depth, but also noted that the record (~100 years) is too short to conclude that Mmax is depth dependent. Many of the Mmax intraslab events in these regions occurred before 1964, before modern worldwide seismograph networks were established. Information on how these events were recorded, the quality of the locations, depths, and magnitude estimates is less certain. When the largest intraslab events in each region were identified an attempt was made to judge the reliability of the event data using additional published sources. In assessing probabilistic ground shaking hazard from such events, the main sources of uncertainty are 1) the recurrence and reliability of the Mmax estimate given the short instrumental record, 2) whether the larger (M 8.0–8.5) events in the 400–700 km depth range can also occur in the 100–400 km range, and 3) whether current ground motion prediction equations can be extrapolated to M8+ in the absence of strong motion recordings.

Development of 2014 U.S. National Seismic Hazard Maps and Their Implementation in Engineering Applications

Poster Session · Thursday · 1 May · Cook/Arteaga

NGA-West2 Horizontal Ground Motion Model: Comparison of CB08 and CB14

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We summarize the development of the Campbell-Bozorgnia NGA-West2 (CB14) empirical ground motion prediction equation (GMPE) and compare it to our previous 2008 NGA-West1 (CB08) model. We used the extensively updated PEER NGA-West2 database to update CB08 for the 'average' (RotD50) horizontal components of PGA, PGV, and 5%-damped PSA at 21 periods ranging from 0.01 to 10 s. We applied our own set of selection criteria to the PEER database, resulting in 15,521 recordings from 322 earthquakes with moment magnitudes (M) ranging from 3 to 7.9. Of these, 7,208 near-source (0–80 km) recordings from 282 worldwide earthquakes were used to develop our base GMPE and 8,313 far-source (80–500 km) recordings from 276 earthquakes were used to model anelastic attenuation. We modified or added several new terms and predictor variables in developing CB14, including an additional magnitude-scaling term to accommodate trends seen in the small-magnitude data; a new hanging-wall term based on ground motion simulations; magnitude-dependent style-of-faulting, hypocentral depth, fault-rupture dip, and between-event and within-event aleatory variability terms; and regionally dependent linear shallow site, shallow sediment-depth; and anelastic attenuation terms. A comparison of CB08 and CB14 indicates that these GMPEs generally give similar ground motion estimates for M>5.5 and distances less than 100 km. The largest differences are at smaller magnitudes, where the extensive new small-magnitude database allowed us to refine our magnitude and distance scaling terms to correct the overestimation that had been observed in CB08. The other significant differences were in the hanging-wall term, where CB14 predicts the highest ground motion over the down-dip edge of the rupture plane, and in the style-of-faulting and hypocentral depth terms, where CB14 indicates that strike-slip and reverse faults have similar ground motion amplitudes with both predicting increasing amplitudes with hypocentral depth.

Alternative Approaches for the National Seismic Hazard Mapping

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The purpose of the national seismic hazard maps is to provide scientific bases for the development of engineering design and other policy considerations such as the

International Building Code and Residential Code in the United States. Therefore, the maps should be scientifically sound. Although a scientific database including locations of active faults and earthquakes, earthquake recurrent intervals, and ground motion attenuations, has been generated through the national seismic hazard mapping project, the national seismic hazard maps produced are not scientifically sound, however, because of the methodology used to produce the maps: probabilistic seismic hazard analysis (PSHA). As a complicated model, PSHA is not consistent with modern earthquake science and contains a mathematical error: equating a dimensionless quantity (the exceedance probability in one year, or the annual probability of exceedance) to a dimensional quantity (the annual frequency or rate of exceedance with the unit of per year). This mathematical error leads to the so-called ergodic assumption: treating spatial uncertainty of ground motions as an uncertainty over time at a single point. PSHA is scientifically flawed and its results (i.e., hazard curves and maps) are artifacts and difficult to understand. Thus, uses of the national seismic hazard maps are problematic. Alternative approaches are need in order to utilize the scientific database and produce seismic hazard maps that can be readily used to develop engineering design and other policies. One of such alternative approaches is scenario/deterministic seismic hazard analysis. The scenario/deterministic maps are scientifically sound and easy to understand. Furthermore, the scenario/deterministic maps have been used in coastal California and Kentucky.

A Fault-Based Model for Crustal Deformation in the Western United States and Its Application to Seismic Hazard Analysis

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Geodetic data have been collected over the past several decades and the consensus from the seismological and geodetic communities are that the national seismic hazard map (NSHM) models should incorporate those data. In previous NSHM models, slip rates were assigned based on an expert-opinion evaluation of available geologic and geodetic data with constraints of the total plate rates. This report describes development of crustal deformation model for the Western United States (WUS) using a kinematic fault model to determine fault slip rates based on inversions of GPS observation with geological slip-rate constraints. The model consists of six major blocks with distributed faults throughout the WUS. The boundaries of the blocks align with major faults in California and the Cascadia subduction zone. Faults distributed within the blocks have their geometrical structure and locking depth constrained by the Uniform California Earthquake Rupture Forecast version 3 (UCERF3) and the 2008 USGS NSHM model. Each fault segment slips at a solved-for slip rate beneath a predefined locking depth, except at a few fault segments where shallow creep is allowed. Slip vector continuity at fault nodes or intersections is imposed to regulate slip variability and to simulate block-like motion. The slip distribution is estimated using a least-squares inversion. We constrained our fault slip rates for distributed faults within the UCERF3 geologic bounds or ± half of the geologic slip rates for most of the western US faults. The result shows that the geologic slip rates for the California B-faults and rest of the non-California faults in the western US are consistent with the observed GPS velocity field. Major discrepancies between inverted for rates and geologic consensus rates occur along some of the northern California A-faults, from the Mojave to San Bernardino segments of the San Andreas faults, across Central Nevada, and along the southern segment of the Wasatch fault system.

Update of the Pacific Northwest Fault and Ground-motion Models for the 2014 National Seismic Hazard Maps

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Logic trees for the recurrence of earthquakes on the Cascadia Subduction Zone (CSZ), crustal faults, and ground motion models (GMMs) have been developed from discussions at several workshops held for the 2014 update of the U.S. National Seismic Hazard Maps. At these workshops we assessed alternative models on the location of the down-dip edge of the ruptures of CSZ great earthquakes, rates of large earthquakes along the CSZ, new crustal fault data, and new GMMs. A logic tree for the position of the down-dip edge was developed based on modeling of geodetic and uplift data and the depth of the top of non-volcanic tremor. We model additional M 8+ earthquakes in the southern CSZ based on studies of offshore turbidite data and onshore tsunami deposits and subsidence. Partial CSZ ruptures were modeled with a mean recurrence of about 1000 years in the southern half of the zone. These partial CSZ rupture earthquakes supplement the whole CSZ ruptures with moment magnitudes inferred to range from 8.6 to 9.3 that occur every 500–550 years. We also assessed the earthquake activity rates on crustal faults. We added the Tacoma fault and extended the Whidbey Island fault based on discussions with geologists. After discussions at our GMM workshop, we included 4 subduction interface and deep-intraslab GMMs and included 5 new NGA-W2 GMMs for crustal faults. Resulting hazard at 5 Hz spectral acceleration in the Pacific North West region generally is higher than the 2008 model along the coast of southern Oregon and northern California due to the CSZ changes and somewhat higher in portions of the Puget Sound region due to addition of new faults and changes to the background seismicity models. Ground motions are slightly lower in parts of northern Oregon due to changes in the ground motion models and deep seismic sources.

Effect of Adaptive Smoothing Seismicity Rate Models on Seismic Hazard in the 2014 Update to the U.S. National Seismic Hazard Maps

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The incorporation of adaptive smoothing methods for the calculation of seismicity rate models in the 2014 update to the National Seismic Hazard Maps (NSHMs) for the contiguous United States produces significant changes in seismic hazard across the country. We present the effects of adaptive smoothed seismicity models developed for the NSHMs on probabilistic ground motions with a 2 percent probability of exceedance in 50 years (2%PE50y) at frequencies of 1 and 5 Hz response spectral acceleration because these are the probabilities and frequencies that are most relevant for future updates of the building codes. Seismicity rate models in the NSHMs are developed separately for California (as part of the Uniform California Earthquake Rupture Forecast, v3; UCERF3), the western US excluding California (WUS), and the central and eastern US (CEUS) because of differences in earthquake catalogs and because of the independence of the UCERF3 and NSHM efforts. Construction of the smoothed seismicity models employs the nearest-neighbor-type adaptive method of Helmstetter et al. (2007). This method uses smoothing distances that adapt to the local density of seismicity; adaptive smoothing distances are smaller in regions where seismicity rates are higher. In the WUS and CEUS, median adaptive smoothing distances are about the same as the fixed smoothing distances used in previous NSHM updates; however, adaptive smoothing distances range over an order of magnitude. Consequently, the resulting probabilistic ground motions show significant differences from previous NSHMs. Probabilistic ground motions change by up to 0.5 g (5 Hz, 2%PE50y). Effects of adaptive smoothing on seismic hazard are particularly important in and adjacent to regions of high seismicity and where fault-based source models are absent.

Implications of Recent Findings from Bayesian Inversion of GPS Data for Seismic Hazard Assessment in California

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Geodetic data illuminate aspects of crustal deformation relevant for seismic hazard assessment including fault slip rates, the rate and spatial extent of creep, the relationship between regions of aseismic and coseismic slip, and the patterns of moment deficit recovery over multiple earthquake cycles. We investigate these issues through Bayesian inversion of Global Positioning System (GPS) data from northern and central California. Bayesian inversion allows incorporation of a variety of prior information (e.g., nonnegativity), provides the full probability density function for model parameters, and does not require subjective regularization such as spatial smoothing. It is well suited to characterizing uncertainties on parameters like slip rates and creep rates. Realistic uncertainties are required as direct input to hazard assessment through deformation models, for evaluating those models – underlying assumptions, and in follow-on calculations used in time-dependent hazard forecasts.

The following results from our analyses are directly relevant to future California seismic hazard assessments. 1) Using a newly expanded GPS dataset we estimate slip rates for the northern San Andreas, Maacama, and Bartlett Springs faults of 21.5 +/− 0.5, 13.1 +/− 0.8, and 7.5 +/− 0.7 mm/yr, respectively. 2) We infer that creep on the Bartlett Springs seismogenic zone keeps pace with slip on the fault's deeper extension, while Maacama fault creep occurs primarily above 5 km resulting in a moment deficit on the seismogenic zone. 3) The depth extent of creep on strike slip faults, even for a high creep rate, well instrumented fault like the San Andreas at Parkfield, is poorly constrained by GPS data; lack of resolution must be considered in hazard assessment. 4) Spatial patterns of interseismic creep, coseismic slip, and afterslip at Parkfield, in the context of the San Andreas long-term slip rate, indicate persistent moment deficit even in areas that slip during M6 earthquakes.

Probabilistic Tsunami Hazard Mapping

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In recent years, probabilistic approaches to tsunami hazard mapping have become prevalent on both global scale as well as national and even regional levels. We will report on some of the current efforts under way including development of a probabilistic inundation map for the State of California and the planned addition of a tsunami loads chapter in the ASCE 7 Minimum Design Loads. Because these efforts run parallel to the seismic hazard mapping and will be adapted by the same entities, it is imperative that there is as much commonality as possible between the two in terms of input models and methodologies. For instance, we were able to implement the Cascadia source model from the 2014 National Hazard Map for our inundation mapping. We will present these results and discuss how the seismic source characterization was applied and extended in the tsunami hazard model. For Alaska, where the last update of the seismic hazard map was published in 2007, we have chosen to update the original USGS source model to allow for multi-segment ruptures along the mega-thrust. We believe such sources are very significant contributors to the tsunami hazard, both locally (in contrast to the seismic hazard) as well as in all of the Pacific states. We will present our source characterization in some detail, to elicit comments from interested parties and promote discussion of these updates.

We will also outline our procedure for the hazard mapping for both the ASCE and State of California, and present preliminary high-resolution (10 m) inundation maps for several areas in California.

Ground Motion Attenuation Relations for Central US using Hybrid Broadband Synthetics

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Pezeshk et al. (2011) proposed hybrid empirical ground motion prediction equations (GMPEs) for the central and eastern United States (CEUS) using the next generation attenuation (NGA-West) models and updated seismological parameters. In this study, we will produce a new comprehensive framework for using a hybrid broadband synthetic simulation technique for development of the ground motion attenuation relation in the central US. Synthetics in the low frequency and the high frequency parts of time histories are separately calculated through a kinematic and a stochastic approach, respectively. Hybrid synthetics are obtained by implementing matched second order low-pass and high-pass Butterworth filters for the long period and the high frequency synthetics, respectively. The directivity effects will be captured by applying a kinematic model of the earthquake source and a deterministic wave propagation in the generation of synthetics' long period portion.

GMPEs will be computed from simulations of different hypocenter locations and multiple slip models to consider the variability of the parameters. A new set of GMPEs will be generated for a magnitude range of 5.0 to 7.5 and a distance range of 2 km to 200 km. New questions will be compared with the GMPEs proposed by Pezeshk et al. (2011).

Great Earthquakes and Slip to the Trench (Seismological Society of Japan/Seismological Society of America Joint Session)

Poster Session · Thursday · 1 May · Cook/Arteaga

Could a Sumatra-Like Megathrust Earthquake Occur in the South Ryukyu Subduction Zone?

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A comparison of the geological and geophysical environments between the Himalaya-Sumatra and Taiwan-Ryukyu collision-subduction systems reveal closely tectonic similarity. Both regions are characterized by strongly oblique convergent process and dominated by similar tectonic stress regime. In the two areas, the intersection of the oceanic fracture zones with the subduction systems is characterized by a trench-parallel high free-air gravity anomaly feature in the fore-arcs and the epicenter of large earthquakes were located at the boundary between the positive and negative gravity anomalies. This mainshock distribution and high gravity anomalies indicate a strong coupling degree of the intersection area, which is probably induced by a strong resistance of the fracture features during the subduction. Moreover, the seismicity distribution in the Ryukyu area is very similar to the pre-seismic activity pattern of the 2004 Sumatra event. That is, the thrust-type earthquakes with trench-normal P axis occurred frequently in the eastern part of the mainshock, whereas only few thrust earthquakes occurred in the west. Therefore, the aseismic area located west of 128E, in the western Ryukyu subduction zone, could result from the strong plate locking effect beneath the high gravity anomaly zone. By analogy with the tectonic environment of the Sumatra subduction zone, the occurrence of a potential Sumatra-like earthquake in the south Ryukyu Arc is highly suggested and the rupture will mainly propagate westward to fulfill the region of low seismicity (~125E-129E; 23N-26.5N) and may generate a hazardous tsunami.

Can Compaction Further Enhance Inelastic Wedge Failure in Shallow Subduction Zone Earthquakes?

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One of the distinct features of a convergent plate boundary is the continuous flux of sediments carried by the oceanic plate into the subduction zone. Sediments under various pressure and temperature conditions in the subduction zone experience substantial changes that are considered to contribute greatly to the complexities of subduction zone earthquakes. In this work, we focus on the compaction of sediments and sedimentary rocks in the accretionary wedge that are highly porous. Compaction of porous materials in the accretionary wedge was once considered to contribute to the aseismic nature of the plate interface in the shallow subduction zone (Zhang, Davis, and Wong, 1993).

When porous materials are compacted in the undrained condition (as in the rapid loading of earthquake rupture) the pore pressure increases significantly when pore space closes while pore fluids are nearly incompressible, resulting in a much larger pore pressure increase than that by the elastic compression alone. In this work, we will incorporate compaction in our poroplastic model of shallow subduction zone earthquakes (Ma, 2012; Ma and Hirakawa, 2013) by using an end-cap yield criterion (e.g., Wong, 1997). A likely scenario is that material in the wedge is on the verge of compactant failure initially. Compaction induces the pore pressure increase that in turn reduces effective stress and causes shear failure. We hypothesize that compaction can significantly enhance coseismic wedge failure, which will make our wedge-failure mechanism more plausible in explaining well-documented anomalous observations for shallow subduction zone earthquakes, such as slow rupture velocity, large seafloor uplift, deficiency in high-frequency radiation, and low energy-to-moment ratio.

A Joint Seismic and Geodetic Rupture Model for the 2012 Haida Gwaii Earthquake and the Location of Slip on the Interface Relative to the Queen Charlotte Fault

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The October 28th, 2012, Mw7.8 Haida Gwaii earthquake occurred off the coast of northern British Columbia, in the transition region between subduction of the Juan de Fuca plate beneath the North American plate and a transform fault between the Pacific plate and North American plate: the Queen Charlotte Fault System. In the immediate vicinity of the Haida Gwaii earthquake rupture, relative motion between the North American and Pacific plates is more transpressional in nature than to the North, where the Queen Charlotte Fault System has produced several large (M8+) strike-slip earthquakes. The mechanism of the October 28th, 2012, earthquake is indicative of Pacific plate underthrusting beneath Haida Gwaii, showing slightly oblique thrust faulting on a shallowly dipping plane with a strike parallel to the Queen Charlotte Fault.

We will present the results from a joint kinematic rupture inversion using teleseismic body and surface wave data, and InSAR data. We incorporate two RADARSAT-2 differential interferograms calculated from Wide Swath beam images from left and right-looking operations on two ascending orbital tracks with time intervals of 8–10 months. Preliminary results of our inversions indicate a single primary slip region with a width of 100–120 km along trench, from 52.75°N to the South, and a maximum of 5 m of slip. We will conduct Bayesian inversions of the interferogram displacements to further analyze the resolution of the depth of significant slip and in particular whether the rupture is constrained to the shallower part of the subduction interface to the West of the Queen Charlotte Fault.

Relationship between High-frequency Radiation and Asperity Rupture, Revealed by Hybrid Back-projection with Non-planer Fault

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High-frequency (HF) radiation, in general, is generated by abrupt change of rupture front velocity and/or slip-rate. Therefore, analysis of HF waves is crucial to understand the dynamic rupture process of earthquakes. The hybrid back-projection (HBP) method (Yagi et al., 2012) enables us to obtain the detailed spatiotemporal distribution of HF radiation by stacking cross-correlations of observed waveforms with corresponding Green's functions, By using the cross-correlation, the HBP method can mitigate the effects of subsurface structure.

In this study, we developed a new HBP method by introducing a 3D non-planar fault model based on a subducting plate geometry (Tassara & Echaurren, 2012). We applied it to teleseismic P-waveform data (0.5–2.0 Hz) of the 2010 Maule, Chile earthquake (Mw = 8.8) and then compared our result with a coseismic slip distribution obtained by the new waveform inversion (Yagi & Fukahata, 2011).

At the beginning, strong HF radiation is generated near the hypocenter, and then large slip event follows near the site of strong HF radiation. After 30 s, intermediate HF radiation area propagated from south to north, which concentrates along the rupture front obtained by the waveform inversion. Around 60 s, the second strong HF radiation occurs ahead of the rupture front obtained by the waveform inversion at 200 km north from the epicenter, and soon after that the second large coseismic slip event follows at about the same location.

The strong HF radiation events before the large slip events may be understood in the framework of a cascading asperity model (Ide & Aochi, 2005). The precursory strong HF radiation may be generated by the rupture of a relatively small asperity, which contributes to triggering of rupture of a relatively large asperity. Intermediate HF radiation obtained in-between the first and second large slip events may play a key role in the interaction between the south and the north large slip events.

The Occurrence of Two Types of Megathrust Earthquakes in South Central Alaska

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Up to now, it has not been clarified whether the 1964 megathrust earthquake for the south central Alaska part of the thrust was between YAK (Yakutat Plate) & NA (North American Plate) and/or PAC (Pacific Plate) & YAK (Brocher et al., 1994; Freymueller et al., 2008). Berg (1965) recognized the P wave of the 1964 earthquake was divided into two first motions with the second striking N 16° W with a NE dip of 26°, which is the Wrangell subduction part of the earthquake. In 1964, the Patton Bay and Hanning Bay faults in the SW Prince William Sound had reverse uplift (Plafker, 1967). Based on 1964 horizontal displacements (Parkin, 1966), the YAP & NA moved S from the Aleutian subduction zone against the YAP & NA that moved W from the Wrangell subduction zone, causing these reverse uplifts. There is also a clear ENE displacement indicated by this data between YAK & NA for the Prince William Sound. But such movements are lacking to the W where the YAP appears stuck with the NA (Arke et al. 2013). The YAP needs to move NNW, which will happen when a more continental megathrust occurs, which would be principally between YAP & NA. The crust is now folding (Freymueller et al., 2008) as if the NA is indeed separating from the YAK at a wave length of about 200 kms. The crustal fold of the 1964 megathrust indicates the YAK was actually attached to the NA because its maximum fold wavelength was 475 km (Biot, 1961). Therefore, two types of megathrust earthquakes occur in south central Alaska: the 1964 Pacific type, principally between PAC & YAK; and the more continental type, principally between YAK & NA. Based on Knik Arm subsidence events (Reeder, 2012), these two types alternate at about 520 yrs for the Pacific and 380 yrs for the continental. The next megathrust earthquake would be expected in about 330 yrs. Such a continental megathrust would result in reverse uplift on the N side of the Castle Mountain fault.

Induced Seismicity

Poster Session · Thursday · 1 May · Cook/Arteaga

Characteristics of Induced/Triggered Earthquakes During The Guy-Greenbrier Earthquake Sequence (2010–2011) in North-Central Arkansas

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Between August 2010 and June 2011, an intense sequence of induced/triggered earthquakes occurred along the Guy-Greenbrier fault in central Arkansas due to fluid injection at nearby waste disposal wells (Horton, 2012). The previous study was limited to ~1,000 earthquakes having md > ~2.0. Here we present results for the recently updated catalogue of ~16,000 earthquakes that appears complete between 0 <= ml <= 4.1 for the initial part of the sequence between August 2010 and October 20, 2010. The inclusion of the small magnitude events has revealed that seismicity started a month earlier and further north than earlier established using only md >2 events. This has helped in understanding the timing and migration of earthquakes along the fault. During this period of time, the seismicity migrated from north to south illuminating a previously unknown and nearly vertical fault trending ~N20E (~10km long) with two joined segments The seismogenic zone confined mainly within the crystalline Precambrian basement (~3km < z < 7.5km) though some were observed to occur within the lower Paleozoic on the northern end of the fault. Earthquake size distribution is not uniform with depth. The small earthquakes (ml<1.0) concentrate near the upper portion of the fault, and large events (ml > 4.0) occur along the bottom. A b-value of 1.0 was obtained for the updated catalog during this period with the b-value varying between 1.2 and 0.8 for different clusters of events. Preliminary results from cross-correlation of the first-motion of most of the earthquake's P-waves and that of the M4.1 event are consistent with right-lateral strike-slip on a N20E oriented fault. The pattern of seismicity at ~5km depth is coincident with structural geologic features observed within the Fayetteville Shale (at ~1500m depth). Though the genesis of the two may not be fully understood at this time, it does suggest a potential relationship between both.

Earthquake Monitoring in Eastern Canadian Areas with Shale Gas Exploration Potential

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Two eastern Canadian areas have had some shale gas exploration activities in recent years: the Ordovician St. Lawrence Lowlands of Quebec (Qc) and the Carboniferous Basin of southeastern New Brunswick (NB). In these two areas, hydraulic fracturing was done for exploration purposes and involved small volumes of fluids injected over short periods of time. In these two areas, this exploration activity took place a few years ago and is now stopped, either indefinitely (Qc) or until further notice (NB). Over the last few years, additional seismograph stations with broadband seismometers have considerably improved the monitoring capability of the Canadian National Seismograph Network (CNSN).

Both Qc and NB have naturally occurring earthquakes, but at a very low rate of occurrence. For these, focal depths are generally between 7 and 25 km but some shallower earthquakes are also known. For the St. Lawrence Lowlands, we have investigated the possibility that some of the detected earthquakes could be associated in time and in space with the shale gas exploration work conducted between 2006 and 2011. Specifically, we compared earthquake parameters (locations and origin times) and the basic record of well operations (locations and time periods when hydraulic fracturing was performed). For the very few earthquakes that satisfy the time and spatial conditions, seismic waveforms at stations within 100 km from the epicentres are systematically examined for an Rg phase indicative of a shallow source. We will present results for the St. Lawrence Lowlands Region. Our study for the NB region is only starting. In 2012 and 2013, additional stations have been deployed there to improve the regional seismic network's detection level. The improved network can detect events as small as magnitude mN 1.0 in NB, and will provide background information (rates, epicenters, focal depths) on the naturally occurring seismicity.

Seismic Monitoring at the Decatur, IL, Carbon Dioxide Sequestration Demonstration Site

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The viability of carbon capture and storage (CCS) to reduce emissions of greenhouse gases depends on the ability to safely sequester large quantities of carbon dioxide over geologic time scales. One concern is the potential for induced seismicity. We report on seismic monitoring by the USGS at a CCS demonstration site in Decatur, IL. This is the first (and to date only) CCS project in the U.S. employing high-volume carbon dioxide injection into an extensive brine aquifer. Supercritical carbon dioxide is injected at 2.1 km depth into the Mt. Simon Sandstone, a basal aquifer over granitic

basement. The primary sealing cap is the Eau Claire Shale at a depth of roughly 1.5 km. The Illinois State Geological Survey (ISGS) manages the ongoing Illinois Basin – Decatur Project, a three-year project beginning in November 2011 during which carbon dioxide is injected at a rate of about 1000 metric tons/day. Archer Daniels Midland (ADM) manages the nearby Illinois Industrial Carbon Capture and Storage project, which, pending permit approval, will add 2000 metric tons/day to the total injection rate sometime in 2014.

The USGS seismic network, about 8 km in extent, was installed in July 2013 and consists of 12 stations, including three in 150 m boreholes. We derived a one-dimensional velocity model from a vertical seismic profile acquired by ADM and the ISGS to a depth of 2.2 km, tied into acoustic logs from our borehole stations. We use this model to locate events, all of which are within the footprint of our network. We calculate seismic moments by integrating the first pulses of P- and S-wave arrivals of the displacement traces. Moment magnitudes of these events range from Mw = −0.81 to 1.15. These events tend to group into two distinct clusters: 0.4 to 1.0 km NE and 1.8 to 2.6 km WNW from the injection well. Most of these microearthquakes have been located in the granitic basement, well below the caprock, and are unlikely to have compromised the integrity of the seal.

Microseismic Network Performance Estimation: Comparing Predictions to an Earthquake Catalogue

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The design of networks for monitoring induced seismicity is of critical importance as specific standards of performance are necessary. One of the difficulties involved in designing networks for monitoring induced seismicity is that it is difficult to determine whether or not the network meets these standards without first developing an earthquake catalog. We develop a tool that can assess two key measures of network performance without an earthquake catalog: location accuracy and magnitude of completeness. Site noise is measured either at existing seismic stations or as part of a noise survey. We interpolate measured values to determine a noise map for the entire region. This information is combined with instrument noise for each station to accurately assess total ambient noise at each station. Location accuracy is evaluated according to the approach of Peters and Crosson (1972). Magnitude of completeness is computed by assuming isotropic radiation and mandating a threshold signal to noise ratio (similar to Stabile et al. 2013). We apply this tool to a seismic network in the central United States. We predict the magnitude of completeness and the location accuracy and compare predicted values with observed values generated from the existing earthquake catalog for the network. We investigate the effects of hypothetical station additions and removals to a network simulating network expansions and station failures. We find that the addition of stations to areas of low noise results in significantly larger improvements in network performance than station additions to areas of elevated noise, particularly with respect to magnitude of completeness. Our results highlight the importance of site noise considerations in the design of a seismic network. The ability to predict hypothetical station performance allows for the optimization of seismic network design and enables the prediction of performance for a purely hypothetical seismic network.

Spatio-Temporal Evolution of Earthquake Clusters in Natural and Induced Seismicity

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Recent increase of seismic activity in the Midwestern US and other areas with hydrocarbon and geothermal production highlights the increased risk posed by human-induced seismicity, which may be especially acute in California and other tectonically active regions. Reducing the risk associated with natural and induced earthquakes requires improved understanding of spatio-temporal variations of seismicity. Our recent studies established the general existence of several main types of seismic clusters (singles, burst-like, swarm-like) that can be robustly detected in natural earthquake catalogs and are correlated with properties of the crust. This provides a platform for defining the regional cluster style (dominant type of cluster statistics) and cluster anomalies (deviations from the average style), and studying their relations to various ongoing loadings, including induced events related to exploration activities, and evolution leading to large earthquakes. Here we analyze natural and induced seismicity of California (including the Geysers, Salton Trough, San Jacinto), Midwestern US, and induced seismicity in the TauTona gold mine in South Africa. We show that the cluster style of areas with dominant induced seismicity (e.g., Geysers, Salton Trough, TauTona) is different from that of areas with dominant natural earthquakes (e.g., San Jacinto). We demonstrate that both natural and induced seismicity follow exponential magnitude-dependent aftershock productivity, with the same exponential index near 1 and intercept that is an order of magnitude larger for natural seismicity. We perform comparative analysis of foreshock productivity as well as general analysis of cluster type with focus on development of large events in induced and natural environments. The results offer several robust statistical characteristics that distinguish natural and induced seismic activity, and could be further explored towards understanding the initiation of large events in different areas.

Geothermal Pumping and Induced Seismicity in California Geothermal Fields

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Geothermal energy is an important source of power. However, an impediment to future growth is a concern over the potential that geothermal production and other pumping technologies can induce earthquakes, as observed in New Zealand, Switzerland, the US and elsewhere. Induced earthquakes in California could potentially trigger large earthquakes on the San Andreas and other major faults. Thus, it is critical to better understand the relationship between geothermal production and induced seismicity.

We examine the relation between fluid volume change and seismicity criteria detailed in Davis and Frohlich (1993) at each geothermal field, and analyze data for other conditions or correlations that imply induced earthquakes have occurred. Initial results suggest that seismicity often increases when a new geothermal field begins pumping, and that there are temporal correlations between fluctuations in net fluid volume and seismicity. Monthly injection and extraction totals for geothermal fields in California are freely available from the California Department of Oil, Gas, and Geothermal Resources. Seismicity data are available from the Waveform Relocated Earthquake Catalog for Southern California (Hauksson et al., 2012), and the Double Difference Earthquake Catalog for Northern California (Waldhauser and Schaff, 2008). Southern California seismicity data are supplemented with Southern California Seismic Network (SCSN) data from 2011–2013 (Hutton et al., 2010).

Precision and Accuracy of Micro-Seismic Event Locations

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Studies of in-situ rock fracture rely heavily on locations of micro earthquakes to determine the geometry and spatial activity of fracture systems. Unfortunately, spatial patterns of estimated micro-seismicity and numerical simulations of over-pressure fracturing have proven difficult to reconcile. In this study we use both synthetic and real data to evaluate precision and accuracy of micro-seismic event locations to improve the utility of micro-seismic bulletins for in-situ fracture studies. Our goal is to achieve location uncertainty on the order of 10 meters. Data used in this study are from the Newberry geothermal field in Oregon. Synthetic data are also based on the Newberry network and event geometry. Synthetic tests show that events can be located within 10 meters of the true location if phase arrival times are measured with a precision of 0.01 second and travel time prediction errors are negligible. Uncertainty of locations determined using our multiple-event micro-Bayesloc software and analyst arrival time measurements (picks) of real data suggest that locations are generally constrained to within 100 meters. Micro-Bayesloc uncertainty analysis entails Markov-Chain Monte Carlo sampling that includes modeling both pick and travel-time prediction uncertainty. Re-picking arrival times – particularly S-waves – after rotation of 3-component seismograms to principle components of particle motion improved both pick precision and reduced spurious measurements, resulting in location uncertainty on the order of 30 meters. We are currently conducting tests to determine whether utilization of a 3-dimensional model of seismic velocity can further reduce location uncertainty of real events to the level of error in synthetic test, i.e. 10 meters. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Examining Induced Seismicity in SE New Mexico in the Vicinity of the Waste Isolation Pilot Plant

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Induced seismicity is a human generated phenomenon that causes a release of seismic stress in the crust through human activities such as surface and underground mining,

impoundment of reservoirs, withdrawal of fuids and gas from the subsurface, and injection of fuids into underground cavities. The New Mexico section of the Permian basin is in an active area of oil and gas production. The region is also the home of the Waste Isolation Pilot Plant (WIPP), a geologic repository for radioactive waste, located just east of Carlsbad, NM, close to the region of active industry activity. Small magnitude earthquakes have been recognized in the area for many years, recorded by a network of short period vertical component seismometers operated by New Mexico Tech. However, for robust comparisons between the seismicity patterns and the injection well locations and rates, improved locations and a more complete catalog over time are necessary. Here we present a revised catalog of earthquakes in this area, with improved locations resulting from the addition of data from the 3-component broadband EarthScope Flexible Array SIEDCAR experiment that operated in the area between 2008–2011. Known events are relocated with the additional phase picks from the SIEDCAR stations and compared with the injection well locations. We also use the known events as templates for a waveform scanning efort to identify additional events that occurred within the time period. This more complete seismicity catalog is then compared with the available monthly injection rates during this time period.

Source Characteristics and Failure Process of Hydraulic Fracturing Micro-Seismic Events Located Within and Below the Target Formation

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We investigate and compare the source characteristics and failure process of two clusters of micro-seismic events induced during a hydraulic fracturing shale completion program: one composed of small magnitude (<-M1) events located within the target formation, typical of hydraulic fracturing treatments, another composed of larger magnitude (>M0) events located below the treatment zone, associated with slip on pre-existing faults. The difference in the failure process of the two clusters, conditioned by fracture strength, local stress and its perturbation mechanism, is reflected in the source signal. The micro-seismic events are well recorded by a hybrid system consisting of large-aperture multi-well-arrays of high-frequency geophones deployed near the source, and arrays of accelerometers and low-frequency geophones deployed near the surface, which captures a larger bandwidth than typical downhole recording systems, thereby allowing for the analysis of the rupture process at various scales. We calculate static and dynamic source parameters, such as stress drops, radiated energy, and seismic efficiency using various time and frequency analysis methods. The clusters follow different scaling relationships with deep events having higher average stress drops. We calculate full moment tensor solutions and determine fracture planes using stress field information. Relative to the regional maximum horizontal stress, deep events have fracture planes orientated close to the optimal failure direction, and in zone events show mostly perpendicular oriented fractures, consistent with tensile mechanisms. We investigate the differences in the two rock weakening processes to injection. We calculate rupture velocities and analyze the energy budget and rupture complexity as it provides constraints on the initiation and healing of the rupture mechanism, where high frequencies relate to fault edge effects and breaking of asperities and low frequencies with the overall slip on the fault.

Comparison of Empirical and Model-Based Matched Field Processing (MFP) Earthquake Detection Techniques at the Newberry EGS Site

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We apply the Matched Field Processing (MFP) earthquake detection method to identify more and smaller microearthquakes at the Newberry EGS site than can be identified using traditional STA/LTA earthquake detection methods alone. The MFP approach uses pre-calculated templates to match the spatial structure of continuous seismic data to a selection of known master templates. We compare the effectiveness of empirical master templates created from previously observed earthquakes with model-based master templates created from computed waveforms.

Using ambient noise correlation (ANC), we created a 3D model of the Newberry site down to a depth of 5km. We collected continuous data for the 22 stations in the Newberry network, together with 12 additional stations from the nearby CC, UO and UW networks. The data were instrument corrected, whitened and converted to single bit traces before cross correlation according to the methodology laid out in Benson (2007). We calculated synthetic seismograms through both an original 1D model and the ANC 3D model using the reflectivity method and the LLNL SW4 code, respectively. We validate the model-based template approach by comparing the synthetic waveforms to actual observed events. Although the 1D synthetics are only able to capture one or two peaks of the actual wavetrain, the 3D synthetics are able to capture significantly more of the complexity of the surface waves. We will compare the results from using the empirical MFP method at the Newberry EGS site with results obtained from using the model-based master templates.

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Seismic Efficiency, Overshoot and Enhanced Dynamic Weaking of Fractures Associated with Stimulation in Heavy Oil Reservoirs

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The objective of this paper is to better understand the different fracturing process of two passive seismic datasets over a 30 month period for two reservoirs, steam injection and water flooding, by investigating radiated energy and seismic efficiency. We calculate the Savage-Wood Efficiency (?sw) and overshoot of microseismic events recorded in two reservoirs with different stimulations. We find under similar geological conditions, the seismic efficiency for steam injection compared to water flooding are unique across the datasets with the implication that temperature and fluid pressure having a different impact on the fracturing dynamics. Reservoir A (steam injection) with 4069 events (Mw = −2.2 top −0.2) are low efficiency ($\nu = 0.01$ to 0.48) and considered in overshoot (€ = 0.1 to 0.5). Reservoir B (water flooding) has much fewer events but greater range of magnitudes (Mw = −1.4 to 1.8); with a combination of low and high efficiency events. There are 1545 events with low efficiency (overshoot = 0.002 to 0.49) and 213 events with high efficiency (undershoot = −415 to 0.49), suggesting enhanced dynamic weakening. Overshoot occurs when the dynamic strength of the fault is relatively higher than final stress acting on the fault and less energy is radiated during fracture. Further to this study, we propose to explore in the effects of fracture efficiency in the failure process and infer changes in fracture energy with other source parameters with event size. Additionally, exploring the dynamic stress drop by determining the peak acceleration and velocity value to calculate the radius of the most energetic asperity and thus maximum stress release; for which we can calculate rupture velocity and interpret changes in the failure process for different reservoir stimulations.

A Study of the Potential for Induced Seismicity Resulting from CO2 Injection at Kimberlina, Southern San Joaquin Valley, California

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As part of the National Risk Assessment Program (NRAP) for geologic sequestration of CO2, a study of the potential for induced seismicity and consequent ground motion is being conducted for Kimberlina, a candidate location in the Southern San Joaquin Valley, California. The goal of this program is to assess the effect of the rates and locations of hypothetical CO2 injection in a predictive model to estimate the potential seismic impacts of induced stresses on the existing faulting regime. A probabilistic framework will be used to explore the production of both induced and tectonic earthquakes. This scheme will be used to guide characterization and monitoring programs prior to any injection program. Our study includes accumulating and estimating geologic and geophysical information of the basin structure and shallow velocity structure (e.g. Vs30), characterization of active and potentially active faults, and modeling the effect of the ambient stress field on the faults.

Integrating this information, ground motion prediction is estimated for some of the most potentially hazardous faults by using several databases and techniques. First, a review of the historical seismicity provides baseline hazard, then ground motion prediction equations (GMPEs) derived from induced seismicity studies at hydrothermal injection sites are modified to include variations in Vs30. In addition, regional tectonic GMPE results are used to develop ShakeMap estimates for potential earthquakes in the Southern San Joaquin Valley.

This research is a multi-laboratory effort in the Department of Energy Complex including Los Alamos, Lawrence Livermore, Lawrence Berkeley National Laboratories and the National Energy Technologies Laboratory.

Characterizing Potentially Induced Earthquake Rate Changes in the Brawley Seismic Zone, CA

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The Brawley Seismic Zone (BSZ), located in the Salton Trough of southern California, has a long history of earthquake swarms and geothermal energy

exploitation. Some of these earthquake rate changes may have been induced by fluid extraction and injection activity at local geothermal fields, particularly the North Brawley Geothermal Field (NBGF) and the Salton Sea Geothermal Field (SSGF) (e.g., Chen and Shearer, JGR, 2011; Brodsky and Lajoie, Science, 2013). We explore this issue by examining earthquake rate changes and interevent distance distributions in these fields. For example, in Oklahoma and Arkansas, where considerable wastewater injection occurs, increases in background seismicity rate and aftershock productivity and decreases in interevent distance were diagnostic of fluid-injection induced seismicity (Llenos and Michael, BSSA, 2013). Here we test if similar changes occur that may be associated with fluid injection and extraction in geothermal areas. We use the stochastic Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, JASA, 1988) to detect changes in the underlying seismogenic processes, shown by statistically significant changes in the model parameters. Model changes in the SSGF roughly occur when large changes in net fluid production occur, but a similar correlation is not seen in the NBGF. Also, while increases in both the background seismicity rate and aftershock productivity parameters were associated with fluid-injection induced earthquake rate changes in Oklahoma and Arkansas, in the BSZ only the background rate increases significantly, which tends to correspond with net fluid production rate increases. Moreover, in both fields the interevent spacing does not change significantly with the start of field operations in 1982. This suggests that geothermal field activities may not significantly change the physics of earthquake interactions, but earthquake rates may still be driven by fluid injection or extraction rates, particularly in the SSGF.

Extreme Shallow Earthquakes in the Sedimentary Basin of Imperial Valley, Triggering of Extensional Faulting by Fluid Injection

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Surface faulting has been discovered in association with a shallow extensional M4.7 earthquake that occurred late in the 2012 Brawley swarm. The earthquake is studied by joint analysis of geodetic data including UAVSAR (Uninhabited Aerial Vehicle Synthetic Aperture Radar) data and leveling measurements along with strong motion waveform data. While the horizontal location of basin earthquakes are well established by dense arrays, accurate depth estimates require either well identified depth phase and/or the development of high frequency surface waves. Both these features are satisfied for this very shallow normal event indicating a centroid depth of 2km which is consistent with the long period waveform inversion of basin stations. Clear surface rupture produced by the earthquake is well recorded by the UAVSAR data and field observations. The joint inversion indicates a bilateral rupture centered at the depth of 2km with maximum slip amplitude of ~30cm and averaged rupture velocity of 1.75km/s which is about 90% of the shear wave speed at the depth of 2km. Subsidence recorded by the leveling data two years prior to the swarm (2009-Nov to 2011-Dec) can be well explained by the aseismic slip on the same fault but located about 2km to the south of the centroid of the M4.7 earthquake, revealing complimentary distributions between seismic and aseismic slips. The spatial correlation between the location of geothermal injection wells and the subsidence along with coulomb stress analysis from previous swarm activity suggests the possibility of multiple triggering mechanisms for this shallow extensional event.

Estimation of Seismic Hazard Due to Induced Seismicity Related to Deep Geothermal Wells

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During development and operation of deep geothermal wells fracture processes can occur at different scale which are associated with induced seismicity. Cold fluid is injected into the well and heated fluid is pumped out, so that the rock is exposed to injection pressures and thermal stresses. Thus cracks may be generated or expanded which can be detected as microseismic activity using local seismometer networks. The increase of pore pressure on existing fault planes under tectonic stresses may also cause seismic events which can be felt. A similar problem exists in other industrial processes that are related to energy development and in which the pore pressure is changed, e. g. hydraulic fracturing for shale gas development, production of natural gas and crude oil and injection of liquid waste or liquid CO2.

For the planning and licensing, but also for development and operation of the wells (and plants), the impact of induced seismicity in form of possible intensities and ground motions needs to be specified. To achieve this, methods for the estimation of seismic hazard in case of natural seismicity can be modified and applied. In the research project MAGS, Microseismic activity of geothermal systems' funded by the German Federal Ministry of Environment (BMU) a simple model was developed to determine seismic hazard as the probability of the exceedance of ground motion of a certain size. On this basis, the procedures of standards and guidelines of construction dealing with natural seismicity and vibration phenomena could be transferred to the treatment of induced seismicity. Using limiting values from guidelines, e. g. for the feeling of seismic motion or for weak damage of buildings, it is thus possible to specify the probability of exceedance of such values and to decide whether this can be accepted or not. On the other hand the results can be compared to the impact of natural seismicity to evaluate whether the impact of induced seismicity is relevant or not.

Large and Damaging Earthquakes of 2013/2014

Poster Session · Thursday · 1 May · Cook/Arteaga

The ISC Event Bibliography: A Useful Service for Studying Notable Seismic Events

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The International Seismological Centre (ISC) is a not-for-profit organization in charge of the definitive worldwide summary of seismic events (ISC Bulletin). The ISC Bulletin contains parametric data both for natural and man-made seismic events starting from beginning of last century. We linked the information available in the ISC Bulletin to bibliographic records (mostly peer-reviewed journals). This allows us to offer a map-based web service that supports users in selecting references to scientific publications related to either specific events or events in the area of interest. Notably, some of the greatest earthquakes were described in several hundreds of articles published over a period of few years. The journals included in our database encompass a variety of fields in geosciences (e.g., engineering seismology, earthquake seismology, geodesy and remote sensing, tectonophysics, monitoring research, tsunami, geology, geochemistry, hydrogeology, atmospheric sciences, etc.), thus making this service useful in multidisciplinary studies. Currently the ISC Event Bibliography includes over 15,000 individual publications from about 500 titles related to events occurred in last 100+ years. Although many publications for seismic events occurred in 2013 are yet to come, we have already links to references for some notable event like the 20 of April Lushan and the 24 May Sea of Okhotsk earthquakes.

In this contribution we show how the ISC Event Bibliography helps in gathering information about specific seismic events and its usefulness during paper preparation for authors (hence for reviewers and editors in the revision process). We also suggest that the ISC Event Bibliography can be a useful resource to monitoring agencies that provide information on the seismicity of a region soon after a significant earthquake has occurred.

Possibility of the Independence between the 2013 Lushan Earthquake and the 2008 Wenchuan Earthquake on Longmen Shan fault, Sichuan, China

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The relationship between the Lushan Ms 7.0 earthquake occurred on 20 April 2013 and the 2008 Wenchuan Ms 8.0 earthquake is still under debate. One view is that the Lushan earthquake is the strongest aftershock of the Wenchuan earthquake and the converse opinion believes that the Lushan earthquake is an independent event. To clean up this debate, we use the ETAS (Epidemic-type aftershock sequence) model and the stochastic declustering method to obtain the background/independent probabilities of the Lushan earthquake. The results show that, besides triggered aftershocks in its source fault, the Wenchuan earthquake also changed the background seismicity rate in the Lushan region, about 1.3 as the original rate. The proportion of contributions to the occurrence of the Lushan earthquake from the aftershock effect (in the sense of the ETAS model), the increment of

the background seismicity, and the original background seismicity are, respectively, 12%, 50% and 38%. Considering the relaxation of the lower crust and upper mantle, the combined (coseismic plus postseismic viscoelastic) Coulomb failure stress (CFS) changes on the initial rupture point of the Lushan earthquake are brought 0.1∼0.4 bar closer to failure. Thus, we propose the occurrence of the Lushan earthquake was dramatically affected by the Wenchuan earthquake.

Near Field Dynamic, Co-seismic and Post-seismic Deformations Associated with the 2013, M7.8, and 2003, M7.6, South Scotia Ridge Earthquakes Observed with GPS

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The South Scotia Ridge (SSR) left-lateral transform fault defines the Scotia plate's (SP) southern boundary separating it from the Powell Basin (PB), South Orkney Microcontinent (SOM), and the Weddell Sea sections of the Antarctic plate (AP). The SP developed as a space filling accommodation zone for S. America-Antarctica relative motions, mostly during the last 40 m.y. The SSR also hosts several restraining and releasing bends. The SP, PB and SOM have complex evolution histories including large-scale displacement and stretching of the SOM, as well as other continental fragments within the SP, all of which were incorporated into a background of changing sea floor spreading geometries.

The SOM defines an ∼300 km segment of the SSR opposite a section of the SP that is primarily oceanic crust with a few small, stretched continental fragments. Two large earthquakes, M7.6 and 7.8, with aftershock zones largely confined to the northern SOM boundary, occurred on the SSR in 2003 and 2013. Moment tensor solutions show they occurred on faults dipping ∼30 and 45° to the south. The 2013 event was almost pure, left-lateral strike-slip, while the 2003 event was oblique but predominantly strike-slip. This is an unusual combination of fault dip and slip direction. The half duration of both events is also relatively long.

A continuous GPS station on Laurie Island is located at the approximate center, and close to the surface projection, of the finite fault models for the 2013 earthquake. We present co-seismic static offsets and post-seismic transients for both earthquakes from GPS daily position estimates. In addition, the station now records at 1 Hz and we present the GPS displacement seismogram for the 2013 event. This record contains a complex deformation (translation, and static elastic and dynamic seismic wave strains) signal ∼80 seconds long. Based on a finite fault model, forward modeling of the expected, predicted motion, will be presented in a companion paper by Ye et al.

Characterization of Recent Large Earthquakes in Asia from Backprojection Imaging of Regional Seismic Data

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We use regional seismic data (<30deg) from numerous broadband stations downloaded from the IRIS DMC to study a select group of large and damaging earthquakes from 2013–2014 (all Mw6.5+) in Asia. These earthquakes have numerous seismic stations recording in this distance range, a testament to the recent efforts by the many groups focused on this region, which allows us to use backprojection imaging techniques to study source rupture patterns. Furthermore, because of the station coverage for some of these earthquakes, we are also able to study the effect of frequency band choice, backprojection method (conventional and maximum-likelihood), velocity model, and station weighting schemes to improve on the results for multiple phases. Contrasting our backprojection images for both surface waves and body waves and comparing these to finite fault solutions (when available), we find substantial differences that help improve our understanding of how backprojection imaging represents the rupture process for large seismic events.

Mainshock and Aftershock Mechanisms of the $M_w = 7.5$ Craig, Alaska Earthquake of January 5, 2013 from Continuous Moment Tensor Scanning

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Continuous moment tensor scanning of the long-period wave field was initially envisioned by Kawakatsu and has been implemented at the University of Tokyo, the University of California, Berkeley, and Academia Sinica in Taiwan. The inversion scheme is equivalent to the cross-correlation of Green's functions for a grid of potential sources with seismic recordings below around 0.1 Hertz, and the inversions are performed at one second time steps. The algorithm is computationally efficient because Green's functions are pre-computed and stored in computer memory. Because of the schemes ability to rapidly determine the hypocentral location, event origin time, moment magnitude, and mechanism of an earthquake, it is being implemented at the Alaska Earthquake Center, as providing such information to the public is an integral component of the Center's mission. As part of evaluating the effectiveness of the algorithm, we used it to scan the long-period wave-field excited by the January 5, 2013 $M_w = 7.5$ Craig, Alaska earthquake. This strike-slip event ruptured a portion of the offshore Queen Charlotte fault system and was recorded by the regional network on both broad-band instruments and high-rate GPS. The AEC recorded 350 aftershocks from this event in 2013, 20 of which were in excess of magnitude 4.0, the largest being a magnitude 5.8 event. The offshore location of this sequence and consequent sparse station coverage makes it a useful test for the moment tensor scanning technique. By "replaying" the main shock and aftershock recordings for input into the algorithm, we can gauge its effectiveness under less than optimal conditions, and observe the smallest aftershock detectable with this station coverage. Additionally, we examined the efficacy of including high-rate GPS displacements into the data stream, and note that, when recorded near to the source, these data can be effective when weak-motion instruments may be off-scale.

Modeling Large Earthquakes in Realistic Structures; Mw8.3 Sea of Okhotsk Earthquake

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A finite slip model is derived for the 2013 Mw 8.3 Sea of Okhotsk Earthquake (Z=610km), by inverting the calibrated teleseismic broadband P-waveforms (1 to 100s). The path calibration established by the impulsive Mw6.7 aftershock allows the velocity waveform inversion up to 1Hz for direct P-waves. The inversion shows that the earthquake ruptured on a 10° dipping rectangular fault zone (140 km × 50 km) and evolved into a sequence of 4 sub-events (E1-E4). The rupture process can be divided into two main stages. The first propagated south, rupturing sub-events E1, E2 and E4. The second stage (E3) originated near E2 with a delay of 12 s and ruptured northwards, filling the slip-gap between E1 and E2. This kinematic process produces an overall slip pattern similar to shallow swarms, e. g. the 2012 Brawley swarm, except it occurs over a compressed time span of about 30s and without many aftershocks, suggesting that sub-event triggering for deep events is significantly more efficient than for shallow events as discussed previously. Here we examine whole seismograms of the two events at global stations and extend the path calibration procedure to various phases. We find that many of the Pacific Island stations where pP ray paths sample the subducted slab arrived up to 5s earlier relative to direct P along with significant waveform distortions. Many of these features can be modeled with 2D slab structure to complement calibrated features. Generalization of the Cut-And-Paste code using whole corrected records proves efficient in recovering accurate source parameters with only a few stations as demonstrated for this large event.

Puerto Rico M6.4 Earthquake of January 13, 2014: PGA & IMM Distribution in the Island

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On January 13 2014, 04:01:04.0 UTC, an MW 6.4 earthquake occurred in the Caribbean Region just about 57 km out of the north coast of Puerto Rico (PR). According to the USGS and PRSN the reported earthquake epicentral location were at Latitude/Longitude of: 19.0010/−66.8480, and 19.13850/−66.82310,

respectively. The focal depth estimated by both agencies was 28 versus 36 km, respectively. During the following 12 hours, 76 aftershocks (USGS source) of magnitude ranging from 2.5 to 4.6 (2 of 4.6, and 2 of 4.5) occurred south of the epicentral region.

The earthquake occurred as a result of oblique-thrust faulting, which is consistent with the subduction zone interface.

Preliminary faulting mechanisms indicate it ruptured either a structure dipping shallowly to the south and striking approximately east-west, or a near-vertical structure striking northwest-southeast. This earthquake occurred in the deep Ocean Trench, it is not the strongest earthquake in the area. The 1918 M7.3, the 1916 M7.2, earthquakes occurred in la Mona Passage and east coast of Dominican Republic, and the 1943 M7.6 just to the northwest are the largest ones occurred nearby the 01/13/2014 earthquake.

Results of the processing (the standard strong motion data processing procedure; .v1, .v2, .v3 was adopted) and analysis of acceleration records collected by the Puerto Rico Strong Motion Program (PRSMP, 65 records) and the inclusion/processing of acceleration records of Puerto Rico Seismic Network (PRSN, 8 records) in terms of the PGA and estimated instrumental intensity IMM are presented in the PR map. The PGA/IMM distribution is discussed in terms of the local site, topographic and possible directivity effects. The site dominant vibration frequency distribution is also discussed.

Response and Fault Characteristics of the Mw6.4 January 13, 2014 Puerto Rico Earthquake: The Largest Event Recorded at the Puerto Rico Seismic Network

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The Mwp 6.4 January 13, 2014 earthquake occurring 75 km north of the Puerto Rico coast is the largest event recorded by the Puerto Rico Seismic Network (PRSN) since its inception in the mid 70's. Moderate size earthquakes such as this one and larger events have been rare in the historic record for the Northeastern Caribbean. Among the most recent large event occurring in the Puerto Rico Virgin Islands region are the Mw7.2 October 11, 1918, and the Mw7.8 July 28, 1943 event. With a network of 20 broad-band seismographs, 10 continuous GPS sites and access to a dozen tide gauges and DART buoys, the PRSN is a multi-observational monitoring network in the northeastern Caribbean, and a leading observatory in the Caribbean. The January 13 event originated at 04:01:01 GMT and had a final manual review location at 19.138 N, and −66.823 E, with a depth of 36 km. With an aftershock distribution of more than 500 events, and a predominantly thrust mechanism, the earthquake must likely reflects contraction along a steep northward-dipping thrust fault. This poster presents two aspects of this event; First is the response of the event (timeline, location, assessment of the threat based on the location and magnitude, and evaluation of the communications with emergency management agencies). Second is the scientific aspect (hypocenter in relation to the tectonic setting, aftershock distribution based on double-differencing relocations and its implications on the rupture zone, waveform inversion to obtain the moment tensor, ShakeMap and CIIM's, and cGPS time series). This event provides the first largest event recorded at PRSN and therefore provides a real-life test to auto-evaluate the outcome of the current earthquakes and tsunami protocols and work towards improvements in case a larger event strikes in the future.

Merging Paths: Earthquake Simulations and Engineering Applications

Poster Session · Thursday · 1 May · Cook/Arteaga

Hybrid Low-High Frequency Ground motion Time Histories for Central US

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A hybrid broadband (HBB) simulation technique is applied to generate a suite of appropriate time histories in the central United States. Long period portion of the simulated ground motions are achieved through a kinematic model of the earthquake source and a deterministic wave propagation. A discrete wavenumber-finite element technique is used to obtain the wave displacement and the velocity time series in the zero to intermediate frequency range. Applying the kinematic source model, the near field effects and the forward directivity in the long period synthetics is captured for a set of station along the strike of the fault. The point source stochastic synthetic, using the computer program SMSIM (Boore, 2005), is used to compute the high frequency part of the synthetic ground motions. Finally, hybrid synthetics are obtained by implementing matched second order low-pass and high-pass Butterworth filters for the long period and the high frequency synthetics, respectively.

The discussed HBB simulation technique is used to generate ground motions for earthquake magnitudes ranging from 4.5 to 7.5 for the central United States region. The HBB ground motion spectral accelerations at 0.2 and 1.0 seconds are compared with the existing ground motion prediction equations (GMPEs) for the central United States region.

Merging Paths: Earthquake Simulations and Engineering Applications

Synthetic Strong Ground Motion from a Scenario Earthquake in a Region of Sparse Seismological Data: Xanthi, N. Greece

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One of the most challenging topics in engineering seismology is the prediction of strong ground motion at regions of sparse seismological data. The town of Xanthi in Northern Greece, is located in the zone of the lowest seismic hazard (ground acceleration coefficient of 0.16g) according to the national building code. However, it is situated next to the most prominent seismotectonic feature of the area, which is the Kavala-Xanthi-Komotini fault. Although neotectonic, morphotectonic and other geological information agree on the active character of the specific fault, instrumental seismological data related to it are almost inexistent. However, this fault is believed to be related to large magnitude, destructive historical earthquakes. Within the THALES project on site classification in Greece, we present an approach to provide synthetic strong ground motion within the area covered by the built environment of Xanthi. We re-assess the seismic hazard through the probabilistic approach and select the examined earthquake scenario (M5.9 at 3 km from the town center) based on the results of hazard de-aggregation. We use the COMPSYN code to simulate low frequencies (up to 3–4 Hz), after validating it with data from recent large earthquakes in Greece. The semi-analytical results of COMPSYN are then combined with stochastically simulated acceleration time histories produced by EXSIM_DMB to provide a hybrid output. Site effects within the town of Xanthi are encountered by incorporating detailed V_S profiles determined within the frame of the THALES project.

Merging Paths: Earthquake Simulations and Engineering Applications

The Ambient Seismic Field Captures Complex Sedimentary Basin Effects

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Seismic hazard in urban environments can be strongly affected for cities that are situated in sedimentary basins. Metropolitan Tokyo is subject to high seismic hazard because it is located above the active junction of three major plates, and because the Kanto sedimentary basin underlies the area. The Kanto basin is fairly deep, and has poorly consolidated, low wave speed sediments, which yield a resonance frequency that approaches the natural period of very tall buildings. It is difficult to model basin effects with confidence because complexities of basin excitation and resonance depend on the details of three-dimensional basin structure, which are incompletely known. The ambient seismic field contains wave propagation information, and provides a new approach for characterizing basin effects in ground motion. We use the ambient field to construct the Earth's response to an impulsive force by combining data from MeSO-net (the Metropolitan Seismic Observatory Network), which consists of 296 shallow borehole instruments in the Kanto basin to act as receivers, and 450 stations from the Hi-net (High Sensitivity Seismograph Network), which are deep borehole stations, to act as virtual sources. We find that at the natural resonance of 5–6 s, the amplification is proportional to sediment thickness. We also explore the impact of the basin shape on the wave field. We find, for example, strong Rayleigh-to-Love wave conversions at the basin edge, and evidence for basin-edge effects in propagation as well.

Merging Paths: Earthquake Simulations and Engineering Applications

Ground Motion Similarity and Coherency between Total and Effective Stress Analyses

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The performance of structures during earthquakes is strongly influenced by the behavior of the soils that support them. Local site effects can influence structures performance in two primary ways: by imposing additional deformations through ground failure and by modifying the ground motion. The reliable and economical seismic design of structures requires that local site effects on the ground motions be accurately predicted. The excess pore pressure generation and consequent reduction in effective stress leads to the softening of a liquefiable soil deposit. This softening can alter the ground motion in terms of amplitude, frequency content and duration.

Models that are written in total stress analysis are the most currently used to simulate the behavior of soils. However, these models do not take into account the excess pore pressure generation and therefore they should not be expected to simulate the changes on the ground motion. Numerous examples on the geotechnical literature show the differences on the ground response modeling using either the effective or the total stress analysis. For weak ground motions, both kinds of analyses provide a similar response. On the contrary, for strong ground motions, in general the total stress analysis overestimate peak accelerations while acceleration amplification for long periods can be underestimated.

The aim of this work is to assess the level of similarity of the free field ground response using a total and an effective stress analyses on a liquefiable soil. The ground motion similarity is evaluated by the Anderson criteria and the lagged coherency. For this purpose a 2D-FE model of a soil profile is considered. The natural hazard is given by real input motions from the PEER Center database with a wide range of acceleration. The ECP elastoplastic multi-mechanism model is used to represent the soil behavior.

Merging Paths: Earthquake Simulations and Engineering Applications

Developing Ground Motions for Tall Buildings in Southern California

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Pacific Earthquake Engineering Research (PEER) Center developed guidelines for tall buildings seismic design as part of the Tall Buildings Initiative (PEER, 2010). Later, Los Angeles Tall Buildings Structural Design Council (LATBSD, 2011) published an alternative procedure for seismic analysis and design of tall buildings. In terms of ground motions, these two publications differ from ASCE 7–10 as they recommend using the geometric mean spectrum and not the Risk-Targeted maximum direction spectrum for the analysis and design of tall buildings in the LA region.

This paper will present examples of two tall buildings in San Diego. Located only two blocks from each other, one is being designed using LATBSD (2011) and the other using ASCE 7–10. The fundamental period of the buildings ranges from 5 to 6 seconds, which require development of spectra and spectrally matched time histories to a period of about 10 seconds. In addition, both of these buildings are located less than 1 km from the Rose Canyon fault system, requiring that rupture directivity and near-source effects should be taken into consideration. Development of response spectra, spectrally matched time histories, ground motion orbit plots, and rotation of ground motions in fault normal and fault parallel directions will be shown to highlight the differences. The authors expect that this paper will be very beneficial to practitioners and help them understand the fundamentals of the differences behind the two approaches.

Monitoring Dynamic Changes at Active Volcanoes and Fault Zones

Poster Session · Thursday · 1 May · Cook/Arteaga

Ambient Noise Monitoring of Temporal Changes in Seismic Velocity at the Geysers Geothermal Field, California

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To monitor the temporal stress change induced by tectonic events or fluid injections at the Geysers Geothermal Field, CA, we search for the small perturbations of the velocity structure by exploiting the correlations of ambient seismic noise. Vertical component of the 15-month-long continuous seismic data are obtained from an array of 30 seismic stations maintained by Lawrence Berkeley National Laboratory. The procedure of the study includes computing hourly cross-correlations of the seismic noise of each station pair and stacking these hourly data into 1-day and subsequently 30-day stacks to obtain a reference Green's function (RGF) with high signal to noise ratio. We identify the relative seismic velocity change (dv/v) within the earth structure by measuring the relative travel time shift between the RGF and the 30-day stacked correlations.

Our result identifies two types of changes in dv/v; (1) a significant decrease in dv/v of 0.3% due to three M3.0+ earthquakes occurred on the same day and (2) a long periodic change in dv/v due to fluid injection or possibly seasonality in ocean microseisms. To further explore the change associated with the local earthquakes, we reduce the stacking time window from 30 days to 1 day to increase temporal resolution. To determine the source of the long periodic change in dv/v, we correlate both the wave height amplitude during our study period, which is proportional to strength of ocean microseisms, and the fluid injection data to the measured dv/v. Additionally, using single value decomposition method, we estimate the spatiotemporal variations in dv/v near stations. An overall improvement in our processing method and inverse model increase our monitoring ability to differentiate the sources that induce change in stress at the Geysers.

Nonlinear Deformation Examples Recorded by the Plate Boundary Observatory

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The Plate Boundary Observatory (PBO) includes 1100 GPS stations distributed across the western US and Alaska. The network has recorded nearly 10 years of deformation, with all raw and processed data available to the scientific community for analysis. During this time the network has recorded a range of geophysical phenomena: long-term tectonic motion, earthquake offsets, post-seismic deformation, and volcanic inflation/deflation. High-rate and real-time GPS additionally record deformation at scales of minutes to seconds, allowing resolution of seismic waves. We present examples of GPS used to track changes in deformation over time at selected fault systems and volcanoes. In southern California, the GPS network recorded the M7.2 April 4, 2010, El Mayor earthquake. We examine static offsets from earthquake slip from daily processing and dynamic offsets from the passage of surface waves. The earthquake was followed by significant post-seismic deformation, and we observe the evolution of GPS velocities, likely the result of post-seismic flow in the lower crust and upper mantle. In Alaska, PBO maintains GPS stations at the volcanoes Akutan, Augustine, Westdahl, and Shishaldin. Measurements indicate ongoing uplift at Akutan and Westdahl, which last erupted in 1992 and 1991, respectively. The uplift was not constant, with episodes of more rapid uplift and spatial variations in rates. Augustine last erupted in 2005–2006 and Shishaldin in 2004; both volcanoes have complex deformation histories with uplift and subsidence, as demonstrated by the GPS time series. These examples demonstrate the utility of PBO data for tracking surface deformation at time scales from seconds to minutes to days to years. All data examined here are available from the UNAVCO PBO web page as RINEX, GPS position estimate time series, and velocity estimate files.

Study of the Site Effects at Cotopaxi Volcano: Construction of a Seismic Activity Index

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Seismic wave amplitudes are mostly modified by the underlying ground and by the topography of the place where they are recorded. There are many techniques commonly used to quantify these effects. In the present work, through the inverse problem methodology and based on a series of measurements, we propose the determination of the parameters of seismic models which contain the information of the site effects. Once the first results about site effects have been obtained, a refinement of these values using IRLS iterative process based on L1 norm was performed. After this refinement, a quick inspection of the confidence levels obtained by the iterative process was executed, which used a Monte Carlo simulation of a set of measurements contaminated with ambient noise following a normal distribution.

The final goal of the site effect calculations is to normalize the seismic recordings of various stations installed at Cotopaxi volcano, and thus to construct

and implement a unified seismic activity index, which will enable visualizing and quantifying the internal dynamics of the volcano. Eventually, the seismic activity index can be used to supplement volcano monitoring, reducing volcanic risk of inhabitants living in danger zones around Cotopaxi.

Explosion Earthquakes during the 2007 Eruption of Pavlof Volcano, Alaska

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Pavlof Volcano on the Alaska Peninsula began to erupt on August 15, 2007 after a 10.7 year repose. Precursor signals consisted of low-frequency earthquakes that began on August 14 and thermal anomalies that were likely coincident with the beginning of the eruption. The mainly strombolian eruptions occurred from a new vent high on the SE flank of the volcano, separate from the NNE vent that had been active over the previous several decades. Seismic activity, monitored by a network of 6 local instruments, consists of low-frequency events, explosion earthquakes, volcanic tremor, and lahar-generated signals. Here we focus on explosion earthquakes. The first such event occurred August 14 at 17:58:16 UT and the last on September 13 at 15:14:00 UT. Events were often embedded in continuous tremor, but could be distinguished by the air waves, which appeared as a high-frequency spikes superimposed on the lower-frequency ground waves. The time differences in the airwaves at different stations are consistent with the acoustic speed of ~330 m/s. Rates were as high as 14 explosion quakes per minute. Steam and ash plumes were generally below 15,000 ft, but rose as high as 20,000 ft on August 29 and 30. We are working to establish whether systematic changes in explosion rates, signal properties, and air-to-ground-wave amplitude ratios correlate with the height and ash content of the plumes. Measurements are corrected for changes in wind speed and direction. AVHRR remote sensing data showed an ash signal on August 29–30, consistent with pilot reports. On August 30 lightning was observed in the plume from Cold Bay, 59 km SW. Compared with recent eruptions of Pavlof in 1981, 1986, 1996, etc., the eruptive activity was of shorter duration (~5 weeks instead of ~3 months) and was somewhat less explosive with no episodes of ash columns to heights of 30,000 ft or more. Instead the 2007 eruption produced significant lahars that reached the Pacific Ocean on the south side of the mountain.

Receiver Function Analyses of Uturuncu Volcano, Bolivia

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Uturuncu Volcano, located in the central Andes near the border between Bolivia and Chile, has been of interest recently because of large-scale and rapid deformation, estimated at one to two centimeters per year over an area that is about 70 kilometers wide. The volcanoes in this region are thought to be fed by the Altiplano-Puna Magma Body (APMB), which previous studies place around 10–20 kilometers depth. The PLUTONS Project deployed 28 broadband seismic stations around Uturuncu Volcano, from April 2009 to October 2012. We present teleseismic receiver functions that were generated using the time-domain iterative deconvolution algorithm of Ligorria and Ammon (1999). These receiver functions are used to better constrain the depths of the top and bottom of this magma body under Uturuncu, as well as the low velocity layer within it. Preliminary results indicate a spatially varying lid depth of between 10 and 15 kilometers. The shallowest depths for this upper boundary seem to be located near the summit of Uturuncu at depths of approximately 7–10 kilometers. These preliminary results also show a lower boundary depth for the low velocity layer between 17 and 24 kilometers. Results here are based on station spacing of 10–20 km and provide higher spatial resolution than previous regional scale studies.

Network Operations and Data Centers

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Datasets for Seismology: ISC, EHB and GT Bulletins, Station Registry, ISC-GEM Catalogue and Event Bibliography

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The International Seismological Centre (ISC) is a non-governmental non-profit-making organization funded by 62 research and operational institutions around the world, including those in the United States: the NSF, USGS, IRIS and the University of Texas at Austin.

The ISC is charged with production of the ISC Bulletin – the definitive summary of the global seismicity based on reports from over 130 seismic networks worldwide. We also distribute the EHB bulletin – a groomed subset of the ISC Bulletin widely used in studies of inner structure of the Earth. Jointly with NEIC, the ISC runs the International Seismic Station Registry (IR). The ISC station codes and event hypocenters are used by IRIS DMC in serving seismic waveform data to its users. The ISC provides a number of additional products including the IASPEI Reference Event list (GT). The ISC-GEM Catalogue is another dataset that was designed to be used for global and regional studies of seismic hazard and risk. The ISC Event Bibliography is an interactive facility to search for scientific articles devoted to both natural and anthropogenic seismic events that occurred within a region and time period of interest. The multitude of ISC data is widely used by the CTBTO and associated community, including that in the United States, charged with monitoring nuclear tests worldwide.

The ISC data are distributed via the ISC and several mirror websites such as those at IRIS DMC, LLNL, University of Tokyo and CTBTO. The ISC has a substantial development program that ensures that its data remain useful for geophysical research.

Field Observation and Quality Control of China Array Project

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Temporally deployed dense seismic arrays have been proven to be powerful tools to explore deep structure. A lot of array observations have been carried out, among them US Array is the most successful. Recently, China launched its seismic observation project – China Array Project to exploring the deep structure of China mainland. This project is hopefully boosting seismic research and hazard mitigation in China. China Array is divided into 7 phases, and will be finish within 15 years. The first phase has finished in 2013. During the first phase 500 broadband seismic stations have been deployed in South-west China with average inter-station distance of 35 km. In the ongoing second phase of China Array, more than 600 stations will be deployed in North-west China. The observations were carried out in various areas as mountanious regions, Gobi, desert and grassland. Some stations suffer from serious temperature variation, thick sediments, frozen, and strong background noises. To meet the unified data standard, we designed various emplacement strategies according to different site status. In this abstract, we reported the field emplacement, data management, and quality control of China Array, one of the largest portable seismic array observations.

Croatian Seismicity Database

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We present the contents and the quality of data on seismicity of Croatia and the neighboring regions (including all of Bosnia and Herzegovina), collected at the Department of Geophyisics in Zagreb since the late 19th century, when systematic seismology research began in Croatia. The latest revision of the database comprises the Croatian Earthquake Catalog (CEC) which currently lists over 65000 earthquakes, the macroseismic digital archive, a collection of fault-plane solutions (FPS) for over 200 events, a large set of onset-times of local and regional phases from Croatian and nearby networks, and various supporting material (photos, reports, questionnaires, calibration records, etc.). Here we concentrate on the catalog and the FPS database only.

The CEC is regularly updated twice a year. The rate of inclusion of new events rapidly increases, and now exceeds 9000 earthquakes/year. We also report on the recent magnitude (re)calibration and the new relation to convert M_L to M_w. Analyses of catalog completeness in time and in space reveals rather large heterogeneity mostly caused by uneven process of densification of national seismological networks, but also by distribution of population and the degree of development of some subregions in the preinstrumental era.

The thoroughly revised earthquake mechanisms database contains the first-polarity FPS that are since recently being routinely computed for most of Croatian earthquakes with magnitudes above about 3.0, as well as the best double-couple parameters of the CMT solutions from various sources. Although the inferred general orientation of P-axes is in agreement with the assumed SW–NE directed collision of the Adriatic microplate and the Dinarides as the main tectonic driving force, observed systematic deviation from this trend in some areas may indicate significant influence of local conditions in modifying the regional stress-field.

The Next Generation of Data Flow at the USGS National Earthquake Information Center (NEIC)

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The USGS NEIC supports global emergency response, earthquake monitoring, and catalog production by acquiring disparate data from more than ninety U.S. and international seismic networks, integrating and processing this data, and then distributing derived and integrated products. Data flowing through the NEIC includes waveforms, station metadata, and a diverse array of event centric products including: locations and magnitudes, moment tensors, phase arrival times, ShakeMaps, impact assessment from Prompt Assessment of Global Earthquakes for Response (PAGER), tectonic summaries, maps, 'Did You Feel It?' felt reports and city/region information. The large scale effort of seamlessly integrating regional to global seismic data in several formats, from numerous organizations, for real-time to historical time periods, to produce high-quality and time-critical earthquake response products is accomplished by several well integrated, 24 × 7 software applications. The integration and data flow across these sophisticated applications is simplified by: providing shared data as services; using standardized and expandable formats; and the use of a modernized common distribution mechanism. The suite of integrated systems generates products that are accessible by the community via several mechanisms for both human and automated computer consumption. Consumers of this data include millions of public users every day, U.S and international disaster responders, critical facilities, and the earth science research community.

The Mexican Seismic Network

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The seismic activity in Mexico, largely confined to the Pacific Ring of Fire, is mainly caused by the interaction between the Pacific, Cocos and Rivera plates with the North America plate. Although the largest percentage of this activity is generated along the Pacific coast, seismicity also extends to the northwest. For those reasons, in 1910 was founded the National Seismological Service (SSN) of the National University of Mexico (UNAM) aiming to provide timely information on the occurrence of earthquakes in Mexican territory.

However, the implementation of the SSN was not enough to explain the level of damage caused, both in population and structures during big earthquakes. That is why in 1960 the Engineering Institute at UNAM initiated the activities for installing an accelerograph network in the subduction zone along the Pacific coast.

An event that changed the general perception about seismic phenomena in our country was the large earthquake of September 19, 1985 (M=8.1). The earthquake emphasized the importance of seismic monitoring instrumentation in Mexico. So, as part of its public policy, the Mexican Federal government through the Ministry of the Interior (SEGOB) signed a collaboration agreement with UNAM in the field of Civil Protection. Regarding earthquakes, it was considered the creation of the Mexican Seismic Network project.

In its first stage, the project was focused in strengthening seismic instrumentation available in the country. In 2010 those activities were finished and the results indicated that the current infrastructure for monitoring earthquakes is insufficient and inadequate. In the currently second stage the project considers the integration into one national network to the various agencies involved in seismic monitoring and also takes into account the modernization and expansion of the national seismic infrastructure, the standardization of protocols and products to exchange information in real time.

Advanced National Seismic System (ANSS) Comprehensive Catalog

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The ANSS Comprehensive Catalog combines real-time and historic data from ANSS members and collaborators into one catalog representing comprehensive data for each seismic event. Although data from all contributors are associated into a combined catalog, individual contributor catalogs remain available. Source parameters and derived data – such as phases, hypocenters, moment tensors, and ShakeMaps – are included and new formats are easily integrated. The catalog preserves all data in its original form, and indexes metadata for searching. The catalog exposes a web service compatible with the International Federation of Seismographic Networks (FDSN) specification, and several tools have been developed to translate these outputs into other formats. A web-based interactive map uses the web service to search catalog data and display results. Researchers can use these tools to find events of interest, and download data for further processing. Advanced users can run the catalog software locally to receive seismic data in real-time.

A New Shallow Water Cabled OBS Network Off Central California

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In November 2013 PG&E and Guralp Systems Ltd. completed the installation of a novel network design of ocean bottom seismometers (OBS) off the coast of central California near Point Buchon. The primary purposes of the OBS network are to monitor in real-time and continuously microreismicity along the Hosgri and Shoreline fault zones, located offshore from the Diablo Canyon Power Plant (DCPP), and to provide on-scale recordings of magnitude 3 and greater events within the DCPP region. The network consists of four stations, placed in shallow water no more than three nautical miles from the coast. Each station contains a three component broadband seismometer (Guralp CMG-3T), a three component accelerometer (Guralp CMG-5T) and a 24-bit digitizer-datalogger. The equipment is housed in a titanium casing, which is covered by a concrete dome weighing more than one metric ton. The dome secures and protects the equipment. The OBS station closest to shore is equipped with a differential pressure gauge attached to the dome. All stations are daisy-chained to one single multistranded cable, which provides shore power to each station. The signals of each station are digitized in-situ and then transmitted via dedicated optical fiber links inside the cable to a shore station at DCPP. From there, the data are streamed in real-time into PG&E's Central Coast Seismic Network Earthworm and ultimately exported into the California Integrated Seismic Network. In addition to the four permanent stations, two portable OBS units equipped with Guralp CMG-40T seismometers were deployed for three months in the same waters. Because the network is installed in shallow water, depths between 60 and 120 m, the action of waves and swell at the sea surface affect the sensor recordings more strongly than deep water installations of OBS equipment. Nevertheless, our initial results show that the network is capable of recording events of magnitude just above 1 at distances of about 25 km.

Remote Calibration Procedures for STS-2s: Example from the STS-2HG for CTBTO at YBH

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Berkeley Digital Seismic Station (BDSN) YBH is also a certified CTBTO Auxiliary Station (AS109). The CTBTO sensor is a Streckeisen STS-2HG triaxial broadband seismometer digitized by a six channel Q330; co-sited are the BDSN sensors, a three-component set of Streckeisen STS-1 broadband seismometers and a Kinemetrics Episensor strong motion accelerometer. Since the request from CTBTO to preform a remote calibration of the STS-2HG to verify its response and sensitivity, we have been exploring the challenges of reliably determining its response from the recorded stimulus and response data. Here, we report here on the procedure and results of the calibration.

The data for calibrating the STS-2HG (s/n 30235) were derived from two sequences of Random Telegraph (RT) stimuli (at 1.25 Hz and at 25 Hz to determine the low and high frequency responses respectively), and one sequence of 1 Hz sinusoid. Each sequence was applied to the triaxial U, V, W component calibration coils through an appropriate series resistance to limit the drive current, but recorded as E, N, Z. The calibration stimulus signals were generated by the Kinemetrics Q330

data logger and both the stimuli and the response were recorded simultaneously with synchronous sampling at 100 sps. The accuracy of the sensitivity as determined by the response to the RT stimuli is limited by the accuracy of the calibration coil motor constant (2 g/A) provided on the factory calibration sheet, and for the STS-2HG is strongly affected by the seismic noise during the calibration. We compared ground motion recorded by the STS-2HG and the co-sited accelerometer and STS-1s to more precisely determine the calibration coil motor constants, and also removed ground noise observed by the STS-1s during the calibration to reduce its affects. We use the calibration data set to explore and demonstrate methods to calibrate a STS-2(HG) sensor recorded by a three channel data logger, where the caligration input cannot be recorded separately.

Large Scale Real-Time GPS Networks, Data Processing Systems and Community Datasets

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UNAVCO has constructed a real-time GPS (RT-GPS) network of approximately 420 GPS stations allowing the collection and distribution of high-rate (1 Hz), low-latency (<2 s) data streams. RT-GPS has the potential to enhance our understanding of earthquakes, seismic wave propagation, volcanic eruptions, magmatic intrusions, movement of ice, landslides, and the dynamics of the atmosphere. Beyond its increasing uses for science and engineering, RT-GPS also has the potential to provide early warning of hazards to emergency managers, utilities, other infrastructure managers, first responders and others. The majority of the streaming stations come from the EarthScope Plate Boundary Observatory (PBO) through an NSF-ARRA funded Cascadia Upgrade Initiative that upgraded 282 stations focused in the Pacific Northwest on top of the original 100 backbone stations located throughout the PBO footprint. Additional contributions from NOAA (~30 stations in Southern California) and the USGS (8 stations at Yellowstone) account for the other RT stations. Based on community based outcomes of a workshop focused on RT-GPS position data products and formats hosted by UNAVCO in Spring of 2011, UNAVCO now provides real-time PPP positions for all 420 stations using Trimble's PIVOT RTX software and for 50 stations using TrackRT at the volcanic centers located at Yellowstone, Mt St Helens, and Montserrat. In addition approximately 15 RT-GPS stations in Southern California have been augmented with accelerometers to facilitate studies producing very broad band waveforms to support earthquake hazard studies. We present an overview of the current UNAVCO RT-GPS system, a comparison of the UNAVCO generated real-time data products, an overview of available common datasets, and plans for future RT-GPS developments.

Automatically Processed Aftershock Sequence for the 2012 Oct 27 Haida Gwaii Earthquake

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The 2012 Oct 27th Haida Gwaii earthquake occurred on the Pacific and North America plate boundary, producing a rich and continuing aftershock sequence. This was an unusual earthquake to occur on a predominately strike-slip fault margin as it showed significant thrust motion and produced a tsunami with a maximum recorded height of 0.76 meters in Maui, Hawaii. The plate vector sits at an approximately 15 degree angle to the plate margin resulting in an oblique convergence partitioned into margin parallel strike-slip on the Queen Charlotte fault and near vertical thrust faulting within the Queen Charlotte Terrace accretionary prism. The first few months of this aftershock sequence have been processed with traditional short-term average/long-term average (sta/lta) based detectors. Those results were used for automatic event locations. The same set of waveform data was also processed with Rosenberger's (2010) singular value decomposition (SVD) incorporated with an S-phase detector. The detections on the rotated traces were assigned as either P or S phases and the events were located using the same location program as was used for the traditional sta/lta detection dataset. The results show a four-fold increase in the returned number of automatically determined origins. These two datasets, and the smaller analyst located dataset, all outline an aftershock region approximately 50 km in width and 100 km in length. Three dimensional visualization of the aftershocks illustrate the structure of the seismicity. A variety of first motion focal mechanisms from the aftershock dataset were determined and compared to the processed datasets. Magnitude estimates are now available for the SVD dataset and Omori plots are compared for all 3 datasets.

Need Data? The IRIS DMC Can Help

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The IRIS Data Management Center (DMC) is the repository and access point for all past and future USArray data, including the USArray data from Alaska, along with data from many other deployments and networks. This presentation will cover the most important data access mechanisms and recent developments. In addition, we will highlight our work related to quality assurance.

Web service interfaces at the DMC provide access to a vast archive of seismological and related geophysical data. These interfaces are designed to easily incorporate data access into data processing workflows. Examples of data that may be accessed include: time series data, related metadata, and earthquake information. The DMC has developed command line scripts, MATLABinterfaces and a Java library to support a wide variety of data access needs. Users of these interfaces do not need to concern themselves with web service details, networking, or even (in most cases) data conversion.

The DMC's core web services are conformant with the standard adopted by the International Federation of Digital Seismograph Networks (FDSN). We have assisted a number of other seismological data centers, primarily in Europe, to install these same service interfaces to their data sets. For the end user this means that the same software can be used to access data from multiple data centers.

Finally, the DMC has been working on a system to calculate quality-related metrics from the raw data in our archive. These measurements are primarily designed to assist in the quantification of quality of the raw time series data. The results will be very useful for network operators to pinpoint problems with their data. Additionally the measurements will be useful to end users in as least two important ways: 1) the measurements themselves can be useful to interpret and 2) as a means to reject bad data prior to input into a processing system.

New Insights into Ground Failure as an Urban Earthquake Hazard

Poster Session · Thursday · 1 May · Cook/Arteaga

Mapping Earthquake Induced Liquefaction Surface Effects from the 2011 Tohoku Earthquake Using Satellite Imagery

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Documenting liquefaction surface effects is necessary both to validate and to refine existing liquefaction models. Post-earthquake liquefaction data collection historically relies on field investigation and is often spatially limited and incomplete (e.g., Chleborad and Schuster, 1990). Areas that are not near centers of population or major transportation routes are often neglected and data collection often only focuses on liquefaction occurrence. Pre- and post-earthquake satellite images enable spatially continuous/exhaustive mapping of liquefaction (e.g., Oommen et al., 2013). We investigate two different techniques for mapping earthquake-induced surface effects of liquefaction for the 2011 Tohoku Earthquake using synthetic aperture radar (SAR) images as well as optical images with very high spatial and spectral resolution. First, we evaluate a method proposed by Ishitsuka et al. (2012) based on SAR interferometry. We use three Single Look Complex images acquired by the Envisat ASAR instrument to form pre- and co-seismic pairs. Next, we detect liquefaction surface effects based on a decrease in interferometric coherence. Second, we evaluate a method based on high resolution optical images. We perform textural classification and change detection analysis on WorldView-2 images. In the second method, we identify liquefaction surface effects based on differences in surface roughness, exposed sediments, and surface moisture. We compare the performance of two methods across different environments such as urban versus rural areas.

The Age of Landslides in Anchorage, Alaska

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Numerous large Holocene landslides exist in Anchorage, Alaska, which are suspected to have been caused by megathrust earthquakes (Hansen, 1965; Schmoll & Dobrovolny, 1974; Reeder, 1974). Mean headscarp slopes of these pre-1964 landslides cluster into five assumed 'degradation with time' groups. Based on subsidence events of the nearby Knik Arm Duck Flats, two types of megathrust earthquakes occur: the Pacific (P) Plate like the 1964 earthquake and a more continental Yakutat (Y) Plate (Reeder 2012 & 2013). Assuming these two types alternate, the following predicted Anchorage megathrust events result: 50P, 570Y, 950P, 1470Y, 1850P ybp etc. These ages agree roughly with actual paleoseismic records for Cook Inlet (Bartsch-Winkler & Schmoll, 1992; Combellick, 1991 & 1994) and Copper River Delta (Carver & Plafker, 2008), except the Delta is missing 570Y and 1850Y. In addition, the average inlet bluff erosion rate for Anchorage is 12 cm/yr (Schmoll & Dobrovolny, 1974 pers. com.). Given a width of up to 200 m for major landslides, it would require about 1700 yrs to remove the headscarp of a large landslide along inlet bluffs. Only the steeper three groups occur in inlet bluffs. Correlating megathrust histories with these slopes result with 36.6° for 570 ybp, 33.6° for 950 ybp and 31.6° for 1470 ybp, which is expected with the known erosion rate. Curve fitting yields 2370 ybp for 29.7° and a surprising 4550 ybp for 26.8°. The extensive headscarp for the Inlet View School at 12th Ave and N St is in this 4550 ybp category, which also correlates with the largest paleoseismic megathrust for the region (Plafker & Lienkaemper, 2012). Of note, this degradation curve does not follow the diffusion model as used for fault scarp degradations (Colman & Watson, 1983). Diffusion models require continuous processes. This is not the case for Anchorage where slopes appear to be a function of 'soil' conditions during and just after earthquakes.

Landslide Hazard Mapping and Quantitative Landslide Hazard Planning Scenario for Aizawl, India

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Aizawl, the State Capital of Mizoram, in northeast India is a densely populated hill top city located in the Western Burmese ranges. Aizawl City is located along the topographic crest and steep limbs of an anticlinal fold in the Burmese fold and thrust belt. Steep slopes, often in concert with heavy monsoonal rainfall, are subject to devastating failure in the form of pervasive landsliding that has dominated the historical geologic hazard record in the region. This active and ongoing geologic process was reinforced most recently on May 12, 2013 when a catastrophic landslide occurred in the Laiputlang area resulting in the destruction of several properties and the deaths of 17 people.

A comprehensive landslide hazard planning scenario was recently created for the City of Aizawl, India. The purpose of the landslide scenario was to estimate the percentage of the total area that will fail under the scenario earthquake. A landslide hazard map was created to estimate the percentage of failure as a function of hazard zone. This estimation is based on theoretical and empirical landslide inventory data as well as from site specific data collected from the study area and the results of our slope hazard calculations. We used both quantitative and qualitative methods to estimate the total landslide area (ALmax) that might fail during a Mw = 7.0 earthquake with PGA = 0.35 in close proximity to Aizawl. Malamud et al. (2004) presents a statistical distribution of landslide areas and landslide volumes by defining a probability density function using three complete landslide inventories. Based on the agreement between these three sets of probability densities a distribution equation is presented from which landslide areas and volumes can be predicted for scenario events (Malamud et al., 2004). The quantitative landslide model is combined with empirical relations of landslide density to calculate a percentage of area expected to fail during the seismic shaking.

Influence of Near Surface Stiffness, Material Type, and Prior Rupture History on Reverse Fault Surface Rupture

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The stiffness of the upper thirty meters of geologic material has been shown statistically to have a strong influence on the propagation of fault rupture to the ground surface for reverse events, based on empirical data from past earthquakes (Moss et al., 2013). To further investigate this, a series of fault box experiments that modeled reverse faulting were run on both sand and clay of varying stiffness. These lab experiments found that a relatively 'soft' material accommodated on average 88% more normalized base displacement than a relatively 'stiff' material, supporting the empirical field data. The material type (sand versus clay) had an even greater impact; with sand accommodating on average 175% more normalized base displacement than clay under similar conditions. When considering prior rupture, virgin material accommodated on average 411% more normalized fault displacement than previously ruptured material. These three variables; near surface stiffness, material type, and prior rupture history have been found experimentally to be strong indicators of the likelihood of surface fault rupture in reverse faulting events. Future research is investigating the numerical modeling of these effects to complement the completed statistical and experimental studies.

Updated Geospatial Liquefaction Model for Global Use

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We present an updated geospatial liquefaction model for rapid response and loss estimation. The original model described in 2013 by Zhu and coauthors was based on liquefaction occurrence/nonoccurrence data from Christchurch, New Zealand and Kobe, Japan. We update the model by including data from 15 earthquakes in the United States and Japan where liquefaction has been observed and mapped. Our approach predicts the probability of liquefaction occurrence as a function of simple and widely available geospatial parameters (e.g., derived from digital elevation models) and standard earthquake-specific intensity data (e.g., ShakeMap produced by the United States Geologic Survey). As a result, our model can be applied around the globe without additional data collection. In this approach, we use geospatial parameters as proxies for important subsurface soil properties. For instance, we use time averaged shear wave velocity over the upper 30 m (V_{S30}) and compound topographic index to model soil density and soil saturation. In the current model, we use the Global Multi-resolution Terrain Elevation Data 2010 to compute the topographic proxies. We evaluate different sampling schemes to improve the accuracy of the model. The model has been tested over a broad range of geospatial environments and can be implemented in global rapid response and loss estimation.

Recent Advances in Ground Motions Simulation Methods and Their Validation

Poster Session · Thursday · 1 May · Cook/Arteaga

Using the SCEC Broadband Platform for Strong Ground Motion Simulation and Validation

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The Southern California Earthquake Center (SCEC) Broadband Platform is open-source scientific software that can generate broadband (0–100 Hz) ground motions for earthquakes, integrating complex scientific modules that implement rupture generation, low and high-frequency seismogram synthesis, non-linear site effects calculation, and visualization into a software system that supports easy on-demand computation of seismograms. The Platform has been developed by a scientific and engineering collaboration that involves geoscientists, civil engineers, graduate students, and scientific software developers.

The Platform operates in two modes: validation simulations and scenario simulations. In validation mode, the Platform runs earthquake rupture and wave propagation modeling software to calculate seismograms of a historical earthquake for which observed strong ground motion data is available. In validation mode, the Platform calculates a number of goodness of fit measurements that quantify how well the model-based broadband seismograms match the observed seismograms. Based on these results, the Platform can be used to evaluate and validate different numerical ground motion modeling techniques. We have recently modified the software to enable the addition of a larger number of historical events, and we are now adding validation simulation inputs and observational data for 20+ historical events from the eastern and western United States, Japan, Taiwan, Turkey, and Italy. In scenario mode, the Platform runs simulations for hypothetical earthquakes. In this mode, users input an earthquake description, a list of station names and locations, and a 1D velocity model for the region of interest, and the Platform software then calculates ground motions for the specified stations.

The Broadband Platform collaborative development process, involving earth scientists, engineers, and software developers, helps ensure that the Platform can be used in earthquake engineering applications.

Evaluation of the Point-Source Stochastic Simulation Method within the SCEC Broadband Platform Validation Effort

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The point-source stochastic simulation method (SMSIM) represents ground motions as a product of simple equations, whose parameters are often derived empirically and therefore are region-specific. Despite being a simple method, the parameters required as inputs retain some physics associated with the effects of the source, path, and site. Although not being formally evaluated within the SCEC Broadband Platform (BBP) Validation effort, results from the recently modified SMSIM have served as a benchmark for comparing the performance of finite-fault numerical methods to simulate pseudo-spectral acceleration (PSa) for use in engineering applications. For this validation exercise, we introduced a new 2-corner source model formulated as the summation of two functions of frequency, representing a generalization of previously published 2-corner models. The new model allows the high-frequency spectral level to be specified by a stress parameter, as it is for the standard one-corner source model. We also accounted for an effective distance, which modifies the single distance used in the point-source simulation to capture the effect of the motions from the extended source arriving from various parts of the fault.

In the presentation, we will provide a brief overview of the new features in SMISM and will discuss the improved ability of the equivalent point-source modeling approach to predict the ground motions from large earthquakes. Calibration of the method by means of comparison with PSa from published GMPEs for two well constrained scenarios shows a considerable flexibility for the new 2-corner source model to approximate a wide range of spectral shapes. Event-specific optimization of the method was achieved by minimizing the bias of simulation results with respect to empirical observations for Western US events.

Validation of the Stochastic Finite Fault Module (EXSIM) Implemented on the SCEC Broadband Platform

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The stochastic finite fault model of Motazedian and Atkinson (2005) and Boore (2009), as implemented in the EXSIM program (www.seismotoolbox.ca) is among the Southern California Earthquake Center (SCEC) broadband earthquake ground motion simulation modules. We calibrate model input elements of EXSIM by comparing pseudo response spectral acceleration (PSA) of ten well-recorded earthquakes in California, Eastern North America, and Japan with the corresponding simulated PSAs. In addition, simulated PSA amplitudes are compared to those of ground-motion prediction equations (GMPEs) from the Next-Generation-Attenuation (NGA) project. EXSIM simulations' average spectral amplitudes are in very good agreement with both event-specific recordings, and with the predictions from GMPEs, over a broad distance and period range, even though we use basic region-specific parameters with no attempt to fit each earthquake individually. The important input parameters are the stress parameter and the attenuation model; an adjustment to the Brune point-source spectrum is made to introduce a 'double-corner' effect (Atkinson and Silva, 1997) that reduces bias at longer periods, particularly for events in California.

We confirm previous conclusions (Motazedian and Atkinson, 2005) that average PSAs from EXSIM simulations don't vary much from one random slip realization to another. The mean bias is correctly reproduced using 5 to 10 realizations for large events ($M>6.5$), while smaller events may need more realizations. The average bias computed from an individual earthquake (comparing EXSIM PSA to recorded PSA), within the 0.1s to 1.0s period band, can be used to infer an event-specific stress parameter. The event-specific stress parameters vary from $\sim$100 to 300bars for study events in California and Japan, and $\sim$300 to 900bars for ENA; however note that the very high stress for ENA is associated with steep near-source geometric spreading.

Refinements to the Graves and Pitarka (2010) Broadband Simulation Method

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Over the past several years, the performance of several ground motion simulation methods has been examined on the SCEC Broadband Simulation Platform (BBP). The analysis utilizes two complementary validation approaches: Part A compares simulated ground motions with recordings from past earthquakes and Part B compares median ground motion prediction equation results for hypothetical earthquakes with predictions from the BBP methods (Goulet et al., 2013). Here, I describe refinements to the Graves and Pitarka (2010) simulation method that have been guided by these studies. One refinement involves the addition of a deep weak zone to the rupture characterization, analogous to the shallow weak zone introduced by Graves and Pitarka (2010). The deep zone begins at 15 km and is characterized by a two-fold increase in the average rise time up to a fault depth of 18 km. Below 18 km, a constant factor of two increase applies. This is accompanied by a reduction in the width of slip tapering along the fault edges. These modifications reduce the radiation of strong motion energy from the deep fault while still allowing large fault displacement to occur in this zone. The result is to reduce the tendency of the simulations to over-predict observed ground motion levels in the period range of 1 to 5 sec, particularly for larger magnitude ruptures ($Mw > 6.5$). A second refinement to the methodology is to add perturbations to the correlation structure for rise time and rupture speed parameterization. The original approach directly correlated variations of rise time and rupture speed with variations in local fault slip. Here, the correlation structure is relaxed such that the variations are randomly selected from a log-normal distribution having a median value that follows the specified correlation with local slip. The effect is to reduce the coherency of radiated motions around 1 to 2 sec period and provide a smoother transition into the stochastic approach used at shorter periods.

The SDSU Broadband Ground Motion Generation Module Version 1.5

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The Southern California Earthquake Center (SCEC) has completed Phase 1 of its Broadband Platform (BBP) ground motion simulation validation, evaluating the potential applications for engineering of the resulting PSAs generated by 5 different methods. The evaluation included part A, where the methods were evaluated based on the bias of simulation results to observations for 7 well-recorded historical earthquakes with source-station distances between 1 and 193 km, and part B, where simulation results for Mw 6.2 and Mw 6.6 strike-slip and reverse-slip scenarios were evaluated at 20 km and 50 km from the fault. The methods were assessed based on the bias of the median PSA for the 7 events in part A, and on a specified acceptance criterion compared to NGA-West2 GMPEs in part B. One of the 5 methods evaluated was BBtoolbox, a hybrid method combining deterministic low-frequency (LF) synthetics with high-frequency (HF) scatterograms (Mai et al., 2010; Mena et al., 2010; V1.4). In the validation exercise, the LFs are generated using 1-D Green's Functions and 50 source realizations from the kinematic source generator module by Graves and Pitarka (2010, 'GP').

However, the results from BBtoolbox V1.4 did not appear to pass the validation exercise. In order to obtain more accurate BB synthetics, we generated BBtoolbox V1.5 which scales the HFs to a theoretical spectral level at the merging frequency (GP, Eq. 10) fixed at 1Hz, rather than the level of the LFs in V1.4. This modification has generated much improved spectral levels at higher frequencies, while we have seen little evidence of artifacts from this technique. In addition, V1.5 introduced a new source time function with rise-time scaled as a function of moment. With these modifications, BBtoolbox V.15 became one of three methods passing the SCEC validation exercise. Here, we describe the details of BBtoolbox V1.5, and show comparisons between BBtoolbox V1.5 synthetics and observations from the validation exercise.

Adapting the Composite Source Model for the SCEC Broadband Platform

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The composite source model is a kinematic source that, while stochastic in nature, can be described with a very small number of parameters. The source is a superposition of subevents (Brune pulses) distributed randomly on the fault, with sizes distributed according to a random realization of the Gutenberg-Richter distribution, and initiation time determined by the rupture velocity and distance from the hypocenter. Green's functions are calculated for a flat-layered structure using the method described by Luco and Apsel. The seismograms are found by combining the source and Green's functions using the representation theorem. While this model has been successful in reproducing the statistical characteristics of ground motions for several earthquakes, adaptation to the SCEC Broadband Platform requires implementation decisions and a systematic procedure for calibration of the model. The key parameters that must be adjusted are the velocity model, the Q model as a function of frequency and depth and the stress drop of the Brune subevents. The velocity model needs sufficient complexity to mimic the crustal waveguide. The site contribution to kappa is matched by adjusting the value of frequency-independent Q in layers shallower than 5 km, within observational limits, to obtain the target value. The distance dependence of kappa is matched by setting the frequency-independent

contribution to Q in layers below 5 km to maintain consistency with observed Q values obtained from regional wave propagation. The effect of frequency dependence in Q is reproduced by the approach to coda generation. Then an optimal subevent stress drop for each calibration event is determined, and trends with magnitude and faulting mechanism are used to find optimal values for modeling future events. A progress report on this ongoing calibration process will be given in the presentation.

Separating Low- and High-Frequency Wave Propagation in Synthetic Broadband Ground Motion Modeling

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Ground motion prediction equations for spectral acceleration in the western US have geometrical attenuation (GA) that is ~1/R (Earthquake Spectra, 2008). However earthquakes simulated in 1D earth models have a larger GA for epicentral distances up to ~70 km (e.g., Burger et al., 1987), This difference is most likely caused by the 1D velocity structure's failure to represent the propagation of high frequency (HF) waves. Consider a finite fault representing the source embedded in a nearly homogeneous region of a 1D model. For epicentral distances greater than the source depth, upgoing rays will have a large angle of incidence when they impinge on the near-surface layers. These rays will then glance off the shallow structure and thus transmit insufficient energy to the surface.

To overcome this effect in 1D models, we have modified the UCSB method for computing broadband synthetics (Liu et al., 2006; Schmedes et al., 2013). We use different velocity structures for HF and low-frequency (LF) propagation. The source remains the same. Liu et al. (2006) includes stitching of synthetics computed using a 1D velocity structure with those from a 3D velocity structure. Following this approach we compute ground motions up to a certain frequency using the full 1D model. We modify the full 1D model by replacing the medium above the Moho with a single elastic layer. Using the same source, we compute full waveform synthetics with the modified 1D model. We approximate the local amplification expected from the full 1D model by applying the quarter wavelength method (Boore & Joyner, 1997). We use wavelets to stitch the HF ground motion, computed with the modified 1D model and local amplification, to the LF ground motion, computed with the full 1D model. With these modifications we recomputed a set of validations used by SCEC. In particular we are interested in eliminating the bias (in the goodness of fit) that changed with distance.

Pseudo-dynamic Source Modeling with 1-Point and 2-Point Statistics of Earthquake Source Parameters

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Ground motion prediction is an essential element in seismic hazard and risk analysis. Empirical ground motion prediction approaches have been widely used in the community, but efficient simulation based ground motion prediction methods are needed to complement empirical approaches, especially in the regions with limited data constraints. Recently, dynamic rupture modeling has been successfully adopted in physics-based source and ground motion modeling. Various forms of pseudo-dynamic source modeling methods have also been developed to benefit from both computational efficiency of kinematic source modeling and physics-based source models. We develop a new pseudo-dynamic source modeling method with 1-point and 2-point statistics of earthquake source parameters. Both 1-point and 2-point statistics are constrained by rupture dynamics and kinematic source models for past events. We generate physics-based kinematic source models for future events by stochastic modeling, honoring target 1-point and 2-point statistics. More importantly, we are now able to quantify the variability, in particular, aleatory uncertainty, of finite source models more rigorously. It is an important issue to quantify the variability of finite source models because seismic hazard might be dominated by the upper bound of the variability. In the framework of 1-point and 2-point statistics, standard deviation (1-point statistics) controls the variability of each source parameter at any given point on the fault while correlation (2-point statistics) controls the shape of the variability in a multi-dimensional space. Our ground motion sensitivity analysis shows that both 1-point and 2-point statistics of source parameters significantly affect near-source ground motion characteristics. Since we are not able to predict future events in a deterministic sense, we believe that it is a valuable effort to quantify the whole possible range of rupture scenarios by constructing a consistent statistical framework.

Broadband Acceleration Time Histories Synthesis by Coupling Low Frequency Seismic Noise and High Frequency Stochastic Modelling

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Information carried by the ambient seismic noise is exploited to extract Green's functions between two seismic stations using one as a "virtual" source. The method developed by Prieto and Beroza (2008) is used and validated by comparing the ambient noise impulse response waveforms with earthquakes of moderate magnitudes from 4 to 6.1 in Japan. As the information is only available at low frequencies (less than 0.25 Hz), the seismic noise approach is coupled with a non-stationary stochastic model allowing to simulate time domain accelerograms from 0 to 50 Hz. This coupling allows the predicted ground motion to have both the deterministic part at low frequencies coming from the source and the crust structure and the high frequency random contribution from the seismic waves scattering. The resulting broadband seismograms show a good agreement with observed ground motions from real earthquakes in the northern Tokyo area in Japan.

Deterministic Simulation of the Mw 5.4 Chino Hills Event with Frequency-Dependent Attenuation, Heterogeneous Velocity Structure and Realistic Source Model

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We present simulations of the 2008 Mw 5.4 Chino Hills earthquake for frequencies 0.1 to 2.5Hz. Our model includes frequency-dependent attenuation with power law $Q(f)=Q_0 f^n$ (Withers et al., 2013), statistical models of small-scale heterogeneities in the medium, and a finite-fault source description (Shao et al., 2012). The background medium is the Southern California Earthquake Center (SCEC) community velocity model version 4 (CVM-4). We generate synthetic seismograms at 14 stations in the Los Angeles Area and perform sensitivity tests on the parameters of the small-scale heterogeneities, guided by analysis of sonic logs. Our results show that key ground motion parameters, such as peak ground velocity (PGV), peak ground acceleration (PGA), cumulative kinetic energy (CKE) and Arias intensity (AI) are affected by the statistical model parameters up to 60% at some stations. End-member tests show that correlation length (L) can change CKE, PGV, and AI by up to 30%. Varying the Hurst exponent (H) from 0.0 to 0.5 causes a slight increase in CKE and AI, but does not result in systematic changes of PGV or PGA. Spectral analysis shows the statistical model primarily affects frequencies greater than 1Hz. Based on comparisons with data, we recommend an attenuation relationship where Q_{S0} =0.10Vs to Q_{S0} =0.15Vs, and statistical models of small-scale heterogeneities with L=150m, H=0.0–0.1 and standard deviations of 5–10%. The statistical models include a horizontal-to-vertical anisotropy factor (~5), based on findings from borehole analysis (Plesch and Shaw, 2013). We find reasonable fits for ground motion parameters and frequency content; however, at some of the stations, particularly on hard-rock sites, the small-scale heterogeneities do not account for the misfit between observed and synthetic seismograms. As a result of this, we conclude the seismic velocities in the upper hundreds of meters are too large in the CVM-4 at these sites.

Sensitivity of Ground Motion Simulation Validation Criteria to Filtering

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The validation of ground motion synthetics has received increased attention over the last few years due to advances in physics-based deterministic and hybrid simulation methods. Validation of synthetics is necessary in order to determine whether the available simulation methods are capable of faithfully reproduce the characteristics of ground motions from past earthquakes. Since a major use of synthetically generated seismograms is in the areas of engineering applications, some validation methods are based on metrics that are oriented towards satisfying specific characteristics such as response spectral shape, duration, and intensity. Particular validation methods involve filtering of signals in order to assess the quality of the fit between synthetics and data within different frequency bands. This allows weighting the contribution of different wavelengths in a physically intuitive way, where the low frequencies are given more weight than the higher frequencies. One particular method of interest is the goodness-of-fit (GOF) criterion introduced by Anderson (2004), where a suit of ten different metrics are combined by frequency bands and ground motion components. We investigate the sensitivity of the GOF criterion to the type and order of band-pass filters used to decompose the original pair of synthetic and data seismograms. We also analyze the consistency and correlation of the results obtained using the various metrics with an alternative time-frequency based misfit criterion. We discuss the implication of the choice of filtering parameters for the composition of results for the case study of a physics based simulation (0–4 Hz) of a past earthquake for which we have a dataset of more than 300 records and offer conclusions about ways to improve future validation of ground motion simulation results.

3D Modeling of Full Waveform Propagation to Evaluate Site Effects on Design Ground Motions at LANL

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The 50-km-long Pajarito Fault System (PFS), extends along the western margin of Los Alamos National Laboratory (LANL). This proximity of LANL to the PFS implies unique ground motion design challenges to LANL with the further complication of the lack of empirical strong motion data in the near field for M 6–7 normal faulting earthquakes. The area is also characterized by a complex subsurface geology consisting of successive basalts flows, volcanic ash deposits and sedimentary units. Both structural features and topography can introduce strong frequency dependent amplification effects. In the last decade, new numerical methods have emerged allowing the modeling of full waveform propagation in complex 3D models. The Spectral Element Method (SEM) is one of the methods achieving remarkable accuracy and convergence performance. In this paper, we present modeling results of wave propagation at LANL using SEM with a 3D seismic model built from available sources of information. A LIDAR model provides surface topography of mesa's and canyons and structural surface. Subsurface structure and stratigraphy are rendered by the 2005 Geologic Framework Model (GFM) developed for the Pajarito Basin for the LANL Hydrogeologic Workplan. The data of 31 regional wells completed since 1998 have been used to constrain transport properties. The SEM uses hexahedra meshes that cannot contain any degeneracies such as zero length edges or zero-volume elements. We construct the meshes selecting basin stratigraphy that form continuous layers without pinching out. All stratigraphic GFM materials are interpolated on to each mesh hexahedra. The result is a stair-step interface except along layers used in the mesh where the hexahedra conform to the stratigraphic layer. Ground motions resulting from different models will be compared. In addition, variability and uncertainty in elastic properties assigned to each GFM material will be explored using alternate seismic source scenarios.

Two Summation-By-Parts Finite Difference Codes for Large Scale Simulations of Seismic Motion

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We report a methodology for finite difference simulations of anelastic seismic motions using the summation by parts (SBP) method. The SBP method provides provably accurate and energy stable solutions. We describe the underlying methodology and two parallelized open- source codes developed for a variety of applications, based on second (WPP) and fourth order (SW4) accurate space and time discretizations.

Our method uses a node-centered discretization of the seismic wave equations in displacement formulation on a structured, or piecewise structured, grid. Our approach is different from the conventional staggered grid used in many seismic FD methods. The node-centered approach allows us to deform the mesh near the free surface to accurately enforce the free surface boundary condition along the actual topography. At depth, mesh coarsening can be used to allow the grid size to increase as wave speeds increase, saving memory and increasing the time step. Mesh generation is automatic allowing for great ease of use to change the domain size, orientation and grid spacing. Absorbing boundary conditions are implemented using a super-grid approach. Attenuation is modeled through a linear viscoelastic reological model using a small number of standard linear solid (SLS) elements coupled in parallel. Three-dimensional (3D) material models can be rendered on the grid in various ways, including hierarchical octree models such as the USGS San Francisco Bay Area model.

The accuracy and convergence of our SBP FD codes is demonstrated by verification against canonical problems and semi-analytical solutions. Parallel scaling properties of our codes will also be reported. Furthermore, we demonstrate the ability of our method, together with a well- developed 3D material model, to predict recorded ground motions for earthquakes in the eastern San Francisco Bay Area. The effect of free surface topography is investigated by computing the response with or without topography.

A New Discrete Representation of Heterogeneous Medium for the Staggered-grid Finite-difference Modelling of Earthquake Motion

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Sufficiently realistic models are necessary for numerical prediction of earthquake ground motion especially in local surface sedimentary structures capable to produce anomalous earthquake motion. It is also obvious that the realistic physical model has to be sufficiently accurately represented by discrete grid models in the (spatial) domain numerical methods such as finite-difference methods.

Recent international comparative exercises for a typical deep Alpine Grenoble valley, France, (ESG 2006) and a shallow sedimentary Mygdonian basin, Greece, (E2VP – Euroseistest Verification and Validation Project 2008–2012) indicated that the existing finite-difference schemes do not reach sufficient accuracy if surface waves are locally induced and propagating along interface with strong velocity contrast.

Recent finite-difference schemes represent a large variety of approaches with considerable differences in accuracy and computational efficiency in realistic models with large velocity contrast and complex geometry of material interfaces. This is mainly due to a level of inconsistency of the various discrete representations of the material interfaces with the boundary conditions at the interfaces.

The E2VP experience led us to improve the existing discrete representation of strong material heterogeneity. We have developed a new discrete representation which is even more accurate than that presented by Moczo et al. (2002) while still consistent with the spatial distribution of particle-velocity and stress-tensor components in the finite-difference staggered-grid scheme.

We briefly present theoretical principles of the new discrete representation and demonstrate its superior accuracy using extensive numerical tests against exact and reliable independent solutions.

GPU-based 3D Simulation of Acoustic Wave Propagation with Complex Topography

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By transferring parallel computations to a high end video card (GPU) we managed to reduce the time of finite difference wave propagation calculations from 11 hours to 27 minutes, an improvement of 95%. This allows us to pursue complex computations without incurring the high costs of large parallel computer clusters or supercomputers. As a first experiment we simulated acoustic wave propagation in an artificial urban environment to illustrate the power of the computational set up. Reverse-time migration is accomplished by propagating a wavefield after reversing the time axis. Using synthetic examples, reverse-time migration of resultant waveforms indicates that we can reasonably reduce the number of stations from 36 to 3 (a 91% reduction) and still achieve a source location solution, although the presence of noise is evident. Application of the reverse-time method using infrasound data in the complex topographic region of Sakurajima volcano, Japan, provides a high resolution localization of the source region. Acoustic pressures from explosive eruptions at Sakurajima were recorded by a temporary network deployed in July, 2013, <7 km from the active vent and amplitudes varied significantly with the crater-station azimuth. Results of numerical modeling are consistent with the observed azimuthal distribution of sound amplitudes, suggesting that scattering and diffraction along the source-to-receiver path geometry is significant. Forward modeling using the GPU-based approach further reveals acoustic nodes of the wave propagation that may be critical to deployment planning. Since topographic relief near volcanoes is often pronounced, scattering and diffraction from topography represents a major part of propagation effects for local infrasound propagation. The GPU-based approach opens new possibilities for exploring 3D wave propagation for testing hypotheses and predicting accurate arrival phases in the presence of wave field distortion.

Seismic Imaging as USArray Moves to Alaska

Poster Session · Thursday · 1 May · Cook/Arteaga

New Data Products at the IRIS DMC

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Since 2009 IRIS Data Management Center (DMC) data products have served the seismology community in a variety of ways with data derived products and tools

to facilitate research. We are expanding our products beyond those derived from traditional seismic data and highlight three new products.

The Noise Toolkit product, available soon, is based on hourly power spectra calculated for broadband (BH) channels at hundreds of global stations. The Noise Toolkit includes polarization attributes of noise, which can help gain insight into the propagation mode of ambient noise. It also measures microseism energy in variable length time windows, making it ripe for data mining and other applications such as 'weather maps' of seismic noise.

The TA Infrasound Reference Event Database (TAIRED) is a user-supported evolving infrasound event database that serves as a reference event depository where researchers can contribute new events, provide alternate solutions for existing natural and man made seismoacoustic sources and find sample infrasound events for their research.

Finally, we are working with the AxiSEM project on a large, multi-terabyte database of 2D axisymmetric SEM Green's functions. We will couple this database with a processing system allowing customizable, on-demand synthetic seismograms. Synthetics will be available for any source-receiver geometry and include attenuation, anisotropy and any source type (e.g. GCMT, point-source, user-uploaded source-time function). These synthetic seismograms will be available via a web service; we will also provide simple and intuitive command line clients to make access easy.

EarthScope's Transportable Array in Alaska

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Since 2003, EarthScope has been installing seismometers in a network, known as the Transportable Array, across the continental United States and southern Canada. The station deployments in the conterminous US were completed in the fall of 2013. In October 2013, and continuing for 5 years, EarthScope's Transportable Array plans to create a grid of seismic sensors in approximately 265 locations In Alaska and Western Canada. The proposed station grid is 85 km, and target locations will supplement or enhance existing seismic stations operating in Alaska. Where possible, they will also be co-located with existing GPS stations constructed by the Plate Boundary Observatory. Stations will utilize the complete sensor suite as in the lower-48 (broadband seismic and atmospheric) with potentially some additional sensors for soil temperature, meteorological and/or strong motion.

We describe the deployment plan and schedule for installation, and details of the engineering concept for the stations. Opportunities for collaborative measurements at TA stations will also be described.

IRIS has installed several experimental stations to evaluate different sensor emplacement schemes both in Alaska and the lower-48 U.S. The goal of these tests is to maintain or enhance a station's noise performance while minimizing its footprint and the equipment, materials, and overall expense required for construction. Motivating this approach are recent developments in posthole broadband seismometer design and the unique conditions for operating in Alaska, where most areas are only accessible by small plane or helicopter, and permafrost underlies much of the region. IRIS has tried different portable drills and drilling techniques to create shallow holes (1–5M) in permafrost and rock outcrops. The results indicate that seasonal changes can affect the performance of seismometers in different ways depending on the emplacement technique. Updates on these results will be described.

Celebrating 10 Years of Delivering EarthScope USArray Transportable Array data from the Array Network Facility (ANF)

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Since 2004, the Array Network Facility (ANF) has been responsible for generation and delivery of the metadata as well as collection and initial quality control and the transmission of the seismic, and more recently infrasound and meteorological data, for the Earthscope USArray Transportable Array. As of January 2014, we have managed data from nearly 1700 stations and are transitioning to operations for the TA in Alaska and the CEUSN project in the Eastern US.

Personnel at the ANF provide immediate eyes on the data to improve quality control as well as interact with the individual stations via calibrations, mass re-centering, baler data retrieval and event analysis. Web-based ANF tools have been developed, and rewritten over the years, to serve the needs of both station engineers and the public. Many lessons on the needs for scalability have been learned.

Real-time feeds of seismic, infrasound, and meteorological data have been available for all TA stations while deployed in the lower 48. Plans for data return when the TA goes to Alaska are still under development. Seismic analysts continue to review all seismic events recorded on 7 or more TA stations making associations against externally available bulletins and/or generating ANF authored locations which are available at both the ANF and IRIS-DMC.

The pressure data available from USArray stations have several unique characteristics that are allowing us to conduct a rigorous analysis of the spatio-temporal variations in the pressure field on time scales of less than an hour across the eastern United States. Deployment of these instruments across Alaska will present a unique dataset.

Flat-Slab Subduction and Whole Crustal Faulting in Alaska: Potential Targets for Earthscope and Joint Active-Passive Seismic Imaging

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Multidisciplinary seismic experiments that include both active-source and passive-source imaging can address fundamental tectonic processes in Alaska. Results from the Continental Dynamics ST. Elias Erosion and tectonics Project (STEEP) provide a powerful example showing that the crystalline crust of the Yakutat Terrane in southern Alaska ranges from 15–35 km thick and is underthrusting the North American plate from the St. Elias Mountains to the Alaska Range (~500 km). Deformation of the upper plate occurs within the offshore Pamplona Zone and onshore Yakutat fold and thrust belts. Deformation patterns, structural evolution, and the sedimentary products of orogenesis are fundamentally influenced by feedbacks with glacial erosion. Recent onshore-offshore active source and onshore passive source models show the Yakutat Moho dips beneath the regions of high-topography within the St. Elias-Chugach Mountains potentially underlying >20 km of tectonically thickened sediments coincident with regions of maximum uplift and exhumation. The Moho dips with increasing steepness towards the Wrangell Volcanic Field reaching 80 km, implying the source of volcanism. The northern, southern, and eastern limits of the Yakutat microplate are strike-slip faults that, where imaged, appear to cut the entire crustal section and may allow for crustal extrusion towards the Bering Sea. Yakutat collison effects on mantle flow, however, have been suggested to cross these crustal features to allow for far-field deformation in the Yukon, Brooks Range, and Amerasia Basin.

Targeted geodetic and seismic deployments as part of Earthscope working within the 'backbone' of the Transportable Array framework could examine all of these features and especially extended observations of lithospheric structure beyond the locations of the STEEP, MOOS, and BEAAR experiments to seek to address fundamental questions about tectonic interactions throughout the northernmost Cordillera and Alaska.

Joint Inversion of Seismic and Gravity Data for Velocity Structure and Hypocentral Locations at Akutan and Makushin Volcanoes

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Joint inversions of geophysical data recover models that simultaneously fit a variety of constraints while playing upon the strengths of each data type. In this study, we combine body wave arrival times with surface wave dispersion measurements and gravity observations to develop a combined 3D P- and S-wave velocity model for Akutan and Makushin volcanoes. P and S arrival times were obtained from local earthquakes recorded by the Alaska Volcano Observatory. Rayleigh wave dispersion curves are derived from ambient noise measurements, and the gravity observations were extracted from the global satellite-based model GGMplus. Although in this case the spatial coverage of the body wave and ambient noise data largely overlap, the joint inversion method is promising for application EarthScope TA data from Alaska, where surface wave data from ambient noise throughout the region and gravity data will complement the distribution of body wave arrival times from local earthquakes.

Preliminary results show that P- and S-wave velocities beneath Akutan are generally reduced at depths shallower than 10 km, below which velocity recovery is poor. The P- and S-wave crustal structure beneath Makushin is more heterogeneous, with a complex pattern of positive and negative anomalies. Captains Bay pluton, 25 km east of the summit of Makushin, shows uniformly high P-wave velocities in the upper 5 km of the crust. These models also highlight the sensitivities of different data types to structure at different wavelengths. Fine-scale structure is recovered by body waves in the most seismically active portions of the model, where the longer-period surface wave data are fit relatively poorly. Meanwhile, the surface wave data are well fit by broad shallow velocity anomalies on the scale of several tens of kilometers in largely aseismic areas of the model. Thus, the combination of data types is crucial to establishing both the long- and short-wavelength features of tomographic velocity models.

Using S Receiver Functions to Investigate Lithospheric and Crustal Structure Below Alaska

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The past 15 years of seismic recordings in Alaska provide a wealth of data suitable to map the depth of crustal and lithospheric interface structure within the North American (NA) and Pacific plates. As Earthscope's Transportable Array moves to the region, a complete view of seismic structure will emerge, yet we can already observe previously undocumented features. Using the S receiver function method that takes advantage of teleseismic S-to-p wave conversions at seismic velocity contrasts, we develop estimates of Moho depths and lithosphere-asthenosphere boundary (LAB) depths across Alaska.

We present receiver gather and a common conversion point (CCP) image volume results to investigate structure that spans multiple tectonic provinces. While the receiver gather approach averages over broad spatial regions (100's of kms), distinct domains are observed. CCP imaging improves the accuracy of depth estimates of continuous 3D structure, and reveals a distinction between the NA and Pacific lithospheric plates. From west to east along strike of the eastern Aleutian subduction zone, the descending Pacific plate is imaged to ~200 km below the western Alaska Range, variably resolved below the central Alaska Range, and appears fragmented to the east at the slab's edge. Strong LAB conversions are present throughout the Yukon-Tanana terrane (100–125 km) and Brooks Range provinces (140–160 km), providing strong contrast against the weaker conversions below the Mesozoic and Cenozoic terranes to the south and west.

Long-term accretionary tectonics and the geometric complexity of the subducting Pacific (plus Yakutat) plate motivate this work. We seek to find a relationship between lithospheric-scale boundaries and geologic provinces, and to observe lateral variations within the Yakutat-bearing portion of the Pacific plate in an effort to understand the relationship between slab edge geometry, recent orogenesis, and the Wrangell Volcanic Field.

Waveform Modeling of Large Earthquakes of the Southern Fairbanks Seismic Zone, Alaska (1929–1947)

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A series of 5 to 6 magnitude > 6 earthquakes occurred within the Northern Foothills Fold and Thrust Belt (NFFTB) and southern Fairbanks Seismic Zone (FSZ) between 1929 and 1947. Fletcher and Christensen (1996) studied the source properties of the October 16, 1947 (M~7.1) FSZ mainshock using teleseismic body wave deconvolution techniques but were unable to obtain a well-constrained focal mechanism for the event. First motion studies of the October 16 mainshock (Wickens and Hodgson, 1967) suggest a northwest striking thrust or reverse fault, a trend that does not match the strike of the FSZ or NFFTB or the strike of features revealed by regional aeromagnetic and gravity data. A preliminary comparison of body waveforms of the January 21, 1929, July 4, 1929, October 7, 1947, and October 20, 1947events indicate they appear to have similar focal mechanisms and depths as the October 16 event. The October 20 and January 21 earthquakes also appear to have similar magnitudes. An event on October 15 appears to be of smaller magnitude since clear body waves are not observed at distances of ~40°. Some earthquake catalogs indicate the July 4, 1929 is larger in magnitude than the January 21, 1929 event; however waveforms of the July 4 event are about 50% smaller than the January 21 event. Earthquake relocations suggest the entire southern FSZ extending from the NFFTB to ~64.5°N ruptured between 1929 and 1947 and that the largest events may have nucleated near east-west trending magnetic highs. Using body waveform data from additional seismograph stations I hope to refine source models for the October 16 mainshock as well as other large events of this sequence.

Seismic Moment Tensors in Southern Alaska Derived from Body Waves and Surface Waves

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We perform a grid search to estimate moment tensors – with uncertainties – for earthquakes in southern Alaska, Mw > 3.5. The earthquakes are parameterized as double couple mechanisms, such that our five inversion parameters comprise four for the moment tensor (strike, dip, rake, Mw) and one for depth. The inversion algorithm is based on the cut-and-paste method of Zhu and Helmberger (1996), which attempts to fit synthetic and observed waveforms for body waves and surface waves by using different bandpass filters and allowing for different time shifts to account for unmodeled 3D structure. We perform detailed comparative tests for 21 events, where we explore the effect of using an L1 norm or L2 norm on the moment tensor solutions and on the uncertainty estimates. We quantify the difference between double couple moment tensor using the angle in matrix space, ω.

For most earthquakes the misfit function in strike-dip-rake space is quite smooth, which causes challenges for generating moment tensor samples of the posterior probability density and for quantifying the uncertainty. We establish a scaling of the misfit function such that it generates 'reasonable' posterior samples. The ω distribution of posterior samples is used to quantify the uncertainty, Ω, such that 95% of the posterior samples have $\omega <= \Omega$. Our uncertainty estimates are considerably larger than those reported in the literature using the same moment tensor algorithm. We have examined over 100 earthquakes in detail and have prepared a moment tensor catalog for southern Alaska. We plan to use this catalog for adjoint tomographic inversion in southern Alaska, following recent efforts in southern California.

Earthquakes of the Minto Flats Seismic Zone, Central Alaska

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The Minto Flats Seismic Zone (MFSZ) is the most prominent seismic feature of central Alaska north of the Denali Fault and one of the greatest seismic hazards to Fairbanks. Interior Alaska is a region of broad, active deformation bounded by the Denali Fault to the south and the Brooks Range to the north. Within this region, there is a series of NNE-striking seismic zones. The Nenana Basin, a 7 km deep, active sedimentary basin, is aligned with one of those seismic zones: the 200 km long MFSZ. This seismic zone contains the highest concentration of deep (>15 km) crustal seismicity in central Alaska. Despite this, the region is relatively unstudied; the three-dimensional fault structure and the relationship between the active sedimentary basin and the subbasin faulting are unknown. Given the proximity to Fairbanks, Alaska's second largest city, it is important to gain a better understanding of the driving processes and seismic hazard associated with the MFSZ. Earthquake locations within the fault zone outline a relatively diffuse region of seismicity. Part of the goal of this study is to produce a more defined image of the fault structure through precise double difference relative relocations of the events. The improved locations are then combined with focal mechanisms for the largest events within five sections of the fault zone, derived using first-motion polarities, body waves, and surface waves. These events reveal consistent left-lateral faulting along the entire fault zone at depths between 10 and 25 km. We examine how deep faulting is related to the ongoing development of the overlying Nenana basin.

Crustal Thickness beneath the Western United States from Virtual Deep Seismic Sounding (VDSS)

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The western United States has a complex tectonic history. Yet, the underlying geodynamic processes are still subjects to debate. In this study, we apply the newly developed virtual deep seismic sounding (VDSS) method to image the crust-mantle interface beneath the western United States, taking advantage of the wide-coverage USArray Transportable Array and much denser regional seismic arrays. VDSS has several inherent advantages over traditional receiver functions and active source seismic reflections and refractions. First, VDSS mainly focuses on the prominent, post-critical reflection, *SsPmp*, which can be as large as the direct S phase. To this end, one high-quality event is usually enough to image the crust-mantle boundary. Second, VDSS is less sensitive to near-surface structures, e.g. sedimentary cover, as the primary *SsPmp* phase is strong enough to overcome such signal-generated noise. Thirdly, when the crust-mantle boundary is gradational in nature, the *SsPmp* phase

still provides a robust estimate of an average crustal thickness, because post-critical reflection is insensitive to details of the reflector.

Results from this study reveal several distinct features of crustal structures in the western United States. We find significant crustal reworking along the Yellowstone - Snake River Plains system, the High Lava Plains, and the transition zone between the Great Basins and the Colorado Plateau. Interestingly, these regions are all characterized by active late Cenozoic magmatic volcanism. In contrast, The Wyoming craton is underlain by a rather thick crust, consistent with its longevity and high elevation. Although the Colorado Plateau is underlain by a thick crust within its interior, its edges, especially the western and southern parts, turn out to be encroached and thinned.

The Wyoming Province and the Llano Province: A Tale of Two Proto-continents

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USArray has facilitated significant advancement in tomographic models and methodologies. While there persists a fundamental tradeoff between horizontal and vertical resolution due to the components of the wave train analyzed, advances in joint inversions are continuing to refine the tomographic images generated with USArray. The DNA13 model incorporates teleseismic P observations, independent SH and SV observations, and surface-wave phase velocities from both teleseismic earthquakes and ambient noise to constrain the relative wave-speed from the crust down into the lower mantle. We address the validity of our models through forward prediction of observables and compare the predictive power of the DNA13 models to other models. In the shallow portion of DNA13, we image the Archean age Wyoming Province, which exhibits evidence of ocean closure at its northern and southern ends. The Llano Province in Central Texas is of Grenville age and still contains lithospheric evidence of subduction as the province accreted to North America. Comparison of these two provinces highlights the role of fossil slabs as part of the cratonic architecture. Analysis of the deep portion of the models highlights variations within the Farallon plate, including two distinct high wave-speed anomalies in the eastern U.S. and a shallow feature in the center of these two anomalies. We propose this is evidence of an oceanic plateau, which provides the necessary positive buoyancy to promote flat-slab subduction of the Farallon plate.

Application of Advanced Multivariate Inversion Techniques to the Western US

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Western USA is an ideal location to test advanced multivariate imaging techniques due to excellent data density provided by the USArray. We simultaneously invert surface-wave dispersion, receiver functions, and gravity anomalies to determine the structure of the crust and upper mantle of the western US. Specifically, our target region spans latitudes from 27 to 54 degrees North and longitudes from 90 to 130 degrees West. Rayleigh and Love surface-wave dispersion data between 5 and 150 seconds come from multiple filter analysis of regional earthquakes. Receiver functions come from the EarthScope Automated Receiver system, and are stacked to produce an average model for each cell in our parameterized region. The gravity observations are extracted from the global EGM2008 model. Our starting model is comprised of an oceanic PREM model west of the Pacific coast, a western US model between that and the eastern front of the Rocky Mountains, and a continental PREM model east of the Rocky Mountain Front. The addition of receiver functions produces sharper boundaries for the observed crustal anomalies. The addition of gravity produces subtle changes to the final model. Our inversion offers a nice compromise between fitting the three different datasets and simultaneously reducing RMS residuals for all. Our final results are consistent with numerous previous studies in the region. In general, the craton exhibits higher velocities than the tectonically active regions to its west. We see high mid-crustal velocities under the Snake River Plain and the Colorado Plateau. In the lower crust we observe lowest velocities in the western Basin and Range and under the Colorado Mineral Belt. At 80km depth we see broad low velocities fanning out from the Snake River Plain likely associated with the mantle plume feeding Yellowstone Caldera. Additionally we see high and low velocity anomalies along the west coast that reflect ongoing subduction processes beneath the western US.

Arc Structure around Mount Rainier From the Joint Inversion of Receiver Functions and Seismic Noise

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The amount and modes of magma transfer from the mantle to the crust along volcanic arcs is poorly understood. To better understand deep arc compositional variations, we analyze the shear wave velocity (Vs) distribution in the crust and uppermost mantle for a set of broad-band stations within 35 km of Mount Rainier, WA, in the Cascades arc. We resolve the depth of the main velocity contrasts using receiver function (RF) analysis. To alleviate the trade-off between depth and velocity intrinsic to RF analysis, we jointly invert them with dispersion constraints from earthquake surface waves (period 20–100 s) and ambient noise (5–20s). A transdimensional Bayesian scheme explores the model space (Vs in each layer, number of interfaces and their respective depths), minimizing the number of layers required to fit the observations given their noise level. Sites away from the forearc trend exhibit a middle-to-lower crust with Vs=3.6 km/s, presumably composed of continent-derived sedimentary rocks from the Puget Group. The Moho is sharp and the uppermost mantle has Vs=4.3 km/s, consistent with dry peridotite. In contrast, stations on the arc trend exhibit a rather fast crust over a slow mantle, yielding a weak Moho. We interpret these sites as magmatically modified. Their distribution correlates with the Southern Washington Cascades Conductor (SWCC) interpreted as partially melted mid-crust. The fast middle-to-lower crust (3.8–4.0 km/s) below the SWCC is consistent with mafic composition, presumably resulting from magma intrusion or chemical differentiation, either in the modern arc or its predecessor. A partially melted peridotite can account for the slow velocity in the uppermost mantle (4.0–4.2 km/s). This agrees with recent observation of large conductor connecting the SWCC to the top of the subducting slab below Mt Rainier, interpreted as flux melting fed by the slab dehydration.

A Joint Local, Regional and Teleseismic Tomography Study of the New Madrid Seismic Zone

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We present new crust and upper mantle 3-D velocity models for the New Madrid seismic zone (NMSZ). The NMSZ is one of the most studied intraplate earthquake zones and, owing to the potential and risk of damaging earthquakes, it is worthwhile to study velocity structure and seismicity in the region. Previous studies of this area using different datasets, inversion methods, resolution and interpretation have provided insight into the velocity structure in this region. This study incorporates a large dataset from three networks – The Cooperative New Madrid Seismic Network (CNMSN) operated by Center for Earthquake Research and Information (CERI), the Earthscope transportable array (TA) and the FlexArray (FA) Northern Embayment Lithospheric Experiment (NELE) project stations – to aid in constructing the most detailed velocity images for the NMSZ to date.

NELE is a lithospheric-scale passive array experiment in the northern Mississippi embayment composed of 6-month deployments of 6 FA stations to fill in the TA grid stations over a period of two years (September 2011 to October 2013) as well as a two-year deployment (July 2013 to June 2015) of 51 broadband seismometers along three profiles with an average station spacing of 20 km. Preliminary work involves the use of data from the FA, TA and CNMSN stations beginning September 2011 to present. The teleseismic body wave arrival times are measured using an Automated and Interactive Measurement of Body Wave Arrival Times (AIMBAT) package (Lou et al., 2012). To date, 137 teleseismic events with magnitude Mw $\geq$ 5.5 recorded by 121 stations have been analyzed yielding a total of 8,574 high-quality P and S wave travel-time residuals. The tomography code TOMOG3D (Dapeng Zhao, 1992), which is designed to use arrival times from local and regional earthquakes and travel time residuals from teleseismic earthquakes is used to derive 3-D P and S wave velocity models for the crust and the upper mantle of this area.

Joint Inversion for Kilauea Volcano with an Edge-Preserving Constraint

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One of the recurring challenges in seismic imaging using different datasets is to find the proper compromise between the different resolutions provided by each dataset.

For example, surface wave data result in smooth models when receiver functions are used to constrain the sharp transitions of the layered structure. We introduce a new total-variation-based regularizer, the Edge-Preserving Constraint, with the ultimate goal of using it for a joint inversion using surface waves, travel-times, and gravity data. The regularizer penalizes noise and artifacts during the inversion while preserving the structural information, and therefore provides blocky models. Our area of application is Kilauea Volcano because of its dense station distribution, and we create a synthetic model by applying an artificial sharp velocity contrast to the area. We develop a numerical algorithm for solving the joint inversion problem with the Edge-Preserving Constraint. We use the developed algorithm on synthetic body-wave travel time data. We compare the results from the newly developed method to conventional body wave tomography with a L2-norm-based damping regularizer, which illustrates the merits of our algorithm. The developed inversion improves the velocity and spatial resolution of the tomography. In comparison with conventional body wave tomography, our method much better preserves the structural information in the resulting tomography, thus yielding sharper reconstructed models.

Low Wave Speed Zones in the Crust beneath the SE Tibet Revealed by Ambient Noise Adjoint Tomography

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We present a refined 3D crustal model beneath SE Tibet from ambient noise adjoint tomography. Different from ray-theory-based tomography, adjoint tomography in this study incorporates a spectral-element method (SEM) and takes empirical Green's functions (EGFs) of Rayleigh waves from ambient noise interferometry as the direct observation. The frequency-dependent traveltime misfits between SEM synthetic Green's functions and EGFs are minimized with a preconditioned conjugate gradient method, meanwhile the 3D model gets improved iteratively utilizing 3D finite-frequency kernels. The new model shows 3 – 6% shear wave speed increasing beneath the western Sichuan Basin (SCB) (depth>15 km) and the central Chuan-Dian Block (CDB), and 6 – 12% shear wave speed reduction in the mid-lower crust beneath the northern and the southern CDB. The inferred spatial pattern of low wave speed zones, consistent with possible partial melt, suggests more complex and disconnected geometry than the pervasive narrow zone from the channel flow models.

Which Receiver Function Features Warrant Geological Interpretation?

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Teleseismic waves can convert from shear to compressional (Sp) or compressional to shear (Ps) across impedance contrasts in the subsurface. These conversions are typically analyzed by deconvolving the parent waveforms from the daughter waveforms to obtain a receiver function that is independent of source-side effects. Several deconvolution techniques have been developed to obtain stable receiver functions in the presence of noise and spectral holes. Sp studies have been especially useful for probing lithospheric structure, since they do not suffer from overprinting of deep signals by shallow-layer multiples. However, their high noise levels motivate the question of which structures are robustly constrained.

To better account for the unknown noise characteristics, we present a method based on transdimensional hierarchical Bayesian inference in which both the noise magnitude and noise spectral character are estimated. We use a reversible-jump implementation of a Markov chain Monte Carlo (rjMCMC) algorithm to find an ensemble of receiver functions that best fit the data while simultaneously inferring the values of the noise parameters. We show that parameterizations typically used to represent noise covariance matrices are suboptimal and propose an alternate parameterization that successfully approximates observed noise characteristics.

We validate the algorithm on actual data as well as synthetic waveforms contaminated with realistic noise. We show that the method retrieves easily interpretable receiver functions even in the presence of high noise levels. We also show that we can obtain useful estimates of noise amplitude and frequency content. Analysis of the ensemble solutions produced by our method can be used to quantify the uncertainties associated with individual receiver functions as well as with individual features within them, providing an objective way for deciding which features warrant geological interpretation.

Topics in Seismology: Hazards

Poster Session · Thursday · 1 May · Cook/Arteaga

3-D Dynamic Analysis of Precariously Balanced Rocks Under Earthquake Excitation

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Analyzing the toppling behavior of precariously balanced rocks (PBR) can provide limits on the largest ground motions (of the type that the rocks are sensitive to) that could have occurred at the rock sites in the time that they have been precarious. We are creating 3-D models of PBRs which are imaged using Terrestrial Laser scanning or photogrammetry techniques. The response of these models to earthquake ground motion is obtained using rigid body dynamics. The rock and the pedestal are considered as separate rigid bodies and the non-penetration constraint between the rock and pedestal is modeled using normal and frictional contact forces. As a proof of concept, we analyzed the 3-D model of Echo cliff PBR located in western Santa Monica Mountains. We used idealized square acceleration pulse (resulting in sawtooth velocity pulse) with varying peak ground acceleration(PGA), time period (T) and number of pulses(n) to characterize the type of ground motion required to topple the rock. We observed that PGA and T are the best indicators of toppling. The PGA required for the rock to start moving changes with the direction of loading and the minimum PGA required to move the rock in any direction is at least 1.75 m/s^2. The PGA required to topple the rock decreases as the time period of the ground motion pulse increases. For example, the approximate PGA required to topple the rock is 22m/s^2 for T=1.5 sec and 3.5 m/s^2 for T=3 sec. We are analyzing the response of the rock to the actual ground motion records used by Purvance et al 2012 to establish the veracity of using idealized ground motions for estimating the response of the rock. We are in the process of creating models and performing similar analyses on several PBRs in Southern California to help improve seismic hazard maps and also to validate ground motion simulations.

Performance of the North Anna Nuclear Power Plant during the 2011 Mineral, Virginia, Earthquake – A Regulatory Perspective

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The North Anna Nuclear Power Station (NANPS) comprises of two nuclear power reactors that began operation in 1978 and 1980. This facility, located about 22 km northeast of the epicenter of the moderate (Mw=5.8) 2011 Mineral earthquake, was the first ever commercial nuclear power facility in the United States to experience a safe shutdown as a result of earthquake-induced ground motion. Although duration of the ground motion was relatively short (i.e., 2 to 4 seconds at different elevation levels in the facility), response spectra developed from recorded ground motions at the reactor containment basemat showed a modest exceedance of the Safe Shutdown Earthquake criteria in both the vertical and north-south horizontal directions. However, safety-related structures, systems and components (SSCs) were not damaged, maintaining their functionality. Only minor damage of some non-safety-related ancillary structures was observed (e.g., wall cracks and minor displacement of dry storage spent fuel casks). This, in combining with other worldwide earthquake experience, demonstrated that nuclear power plants generally perform well given the exceedance of SSE ground motion they experienced. In addition, field investigations performed by the utility and independent researchers and field observations made by NRC staff did not identify a causative surface fault related to the Mineral earthquake either at or immediately adjacent to the plant site. Assessing the existence of a capable tectonic structure at the NANPS nuclear units 1 and 2, using the term 'capable fault' as historically defined was an important part of the deterministic assessment of geologic and seismic criteria at the time the site characterization was conducted for the two units at the NANPS. Therefore, the initial conclusion that no capable tectonic structures existed at the site remained valid.

The Impact of the L'Aquila Trial on the Scientific Community, An Update

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In October 2012, the court of L'Aquila (Italy) sentenced seven experts to six years of jail and ordered them to pay several million Euros in damages to the families of some of the people killed by the Mw 6.3 earthquake on April 6, 2009. Six days before the occurrence of the devastating main shock, the convicted experts participated in a meeting of the National Commission for Forecasting and Predicting Great Risks (CGR) held at L'Aquila.

As already reported at the SSA-meeting 2013, this verdict has a tremendous impact on the scientific community as well as on the manner scientists deliver their expert opinions to decision makers and the society. The aim of the present talk is to give an update on the events related to the trial, that occurred in the past year:

1) After the release of the document describing the court motivations (more than 900 pages), our working group started to contact sociologists, communication experts, jurists and scientists in Geosciences and other disciplines. The aim was to study similar cases, also related to other scientific fields, and to prepare a rebuttal of the weak points in the sentence.

2) The Department of Civil Protection (DCP) financed a research project on short term earthquake precursors.

3) The prosecutor impeached the former DCP-chief (Bertolaso) claiming that he had been the instigator of a (so-called) 'media operation' with the intention of reassuring the population. After hearing the witnesses the same prosecutor recently requested a dismissal of Bertolaso.

4) Last but not least, during 2013, more than 21300 earthquakes occurred in Italy, 70% of them were part of seismic sequences, including 265 M>=3 and 27 M>=4, and no CGR-meeting as the one held in 2009 at L'Aquila was arranged.

Waiting for the beginning of the Court of Appeals we are trying to find any possible way to support our colleagues. Documents, articles and comments about the trial are collected at http://processoaquila.wordpress.com/.

Using Fragile Geologic Features to Place Constraints on Long Term Seismic Hazard

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Marginally-stable rock outcrops and precariously-balanced rocks are collectively termed 'fragile geologic features' (FGFs) and have potential utility for seismic hazard assessment. Establishing the date at which the feature became fragile, usually resulting from irregular erosive wasting of the outcrop, and estimating the amount of seismic shaking necessary to induce its failure, indicates the minimum time elapsed since those shaking conditions were last attained. Key to FGF studies has been the development and ongoing improvements in accuracy of surface exposure dating of rock outcrops using cosmogenic nuclides such as 10Be. A field-based review of previously studied and dated FGF sites in southern California is being undertaken under the auspices of the Southern California Earthquake Centre (SCEC) and is showing that there is a distribution of fragilities across the FGFs. In contrast, previous studies tended to highlight the most fragile FGFs. An emerging view is that constraints on long term seismic hazard should be based on the more representative fragilities observed, rather than relying on the most fragile features. Quartz-rich schist tors in the dry climate and peneplain landscape of central Otago, New Zealand are ideal for surface exposure dating, and FGFs are reasonably common there. FGF studies underway in central Otago are aimed at establishing a range for fragilities in order to provide defensible constraints on seismic hazard, and where possible compare these results to data from other methods, such as trenching and dating of earthquake fault-rupture events.

Defining the Usable Bandwidth for Response Spectra from Records with Different Sampling Rates and Anti-aliasing Filters

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The pseudo-absolute response spectral acceleration (PSA), for response periods from 0.01 to 10 s is the most commonly used intensity measure in ground-motion prediction equations and engineering applications. PSAs are derived from recorded ground motions which have usually been filtered to remove high and low frequencies. Here we are concerned with the removal of high frequencies through the use of anti-aliasing filters. Potential errors on the short-period (high-frequency) response spectral values are expected if the true ground motion has significant energy at frequencies above that of the anti-aliasing filter. This is especially important for areas where the instrumental sample rate and the associated anti-aliasing filter corner frequency are low relative to the frequencies contained in the true ground motions. This is a major concern, for example, for records from the US Transportable Array, especially in the central and eastern United States. We present key results from a recently completed study (Boore and Goulet, 2014) in which ground-motion simulations were conducted to investigate these effects and to develop guidance for defining the usable bandwidth for high-frequency PSA. The primary conclusion is that if the ratio of the maximum Fourier acceleration spectrum (FAS) to the FAS at a frequency f_{saa} corresponding to the start of the anti-aliasing filter is more than about 10, then PSA for frequencies above f_{saa} should be little affected by the anti-alias filter, because the ground-motion frequencies that control the response spectra will be less than f_{saa}. We also briefly address the effect of the time series interpolation method on the computed short period PSA and confirm previous findings that sinc-function interpolation (equivalent to an interpolation in the frequency domain) is preferred to the standard practice of using linear time domain interpolation for the resampling.

Topics in Seismology: Processes

Poster Session · Thursday · 1 May · Cook/Arteaga

Analysis of High-Frequency Icequakes at a Marine-Terminating Glacier in Greenland

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Rapid deformation of fast-moving glaciers leads to the emission of seismic waves from sources internal to the glacier, at the interface between the glacier and the underlying rock or till, and at the glacier's terminus, over a wide-range of frequencies. Small, high-frequency "icequakes" are the most abundant glacial seismic sources, and provide information about glacier dynamics that complement flow data obtained at the glacier's surface using geodetic and remote-sensing methods. At Greenland's large outlet glaciers, long-period signals produced by "glacial earthquakes" during major calving events have been studied systematically. However, little is known about the high-frequency seismic sources within and just beneath these glaciers. We deployed a temporary array of six intermediate-period seismometers around Helheim Glacier in East Greenland with a sampling rate of 100 sps, complemented by a longer-operating broadband station sampling at 20 sps. Helheim Glacier is Greenland's third-largest outlet glacier, and our seven-week dataset contains tens of thousands of icequake signals. We analyze these signals to obtain timing and location information of discrete events, and to consider the relationship between glacier seismicity and other observable glacier-dynamic changes, and we apply our results to better understand the role of brittle deformation in the dynamics of these very large Greenland outlet glaciers. As fast-flowing glaciers such as Helheim Glacier are a primary means of mass-loss for the Greenland Ice Sheet, understanding their dynamics is an important part of the study of ongoing changes in the Arctic.

The Response of Elastic Systems in the Earth to Dynamic Perturbations

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Seismic waves have been observed to perturb the elastic properties of the crust at great distances from the hypocenter. These changes in elastic properties can be observed directly through seismic wave speeds or indirectly by observing changes in the rate and character of seismic emissions and aseismic processes like slow slip, changes in pore pressures, and changes in the packing of granular materials. Characterizing temporal variations in elastic properties is an emerging area of research with important implications for earthquake nucleation processes, earthquake forecasting, and seismic hazards. Here we show that by combining an earthquake catalog analysis with additional observations on temporal and spatial changes in microseismicity, seismic velocities, slip rates, and repeating earthquakes we can observe the signatures of dynamically induced changes in elastic properties in the southern part of the aftershock zone of the 2011 M9.0 Tohoku-Oki earthquake (TOE) following the 2012 M8.6 Indian Ocean earthquake (IOE). In the days following the IOE, several clusters of seismicity in the shallow accretionary wedge are initiated along a north to south trend over 150 km distance, which coincides with a change in behavior of repeating earthquakes on the plate interface and changes in seismic velocities in the

shallow crust onshore. These observations are unique in the post-TOE period and are signatures of a dynamically perturbed elastic system.

Thermal Aging of the Oceanic Asthenosphere

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We investigate the depth extent of mantle thermal aging beneath oceans by averaging S-velocity variations from an ensemble of global tomographic models over equal increments in the square-root of crustal age. Vertical S travel times from these models correlate linearly with the square-root of age across the entire age range, consistent with a half-space cooling model. Using recently published techniques (Jordan & Paulson, JGR 2013), we estimate convergence depths where the age variations become statistically insignificant. We account for the aleatory variability in the S-wave averages using angular correlation functions of the individual tomographic models, correct the convergence depths for vertical-smearing bias using radial correlation functions, and account for epistemic uncertainties through Bayesian model averaging. With 90% confidence, age-correlated variations in S velocities persist to depths greater than 170 km, more than 100 km below the mean depth of the G discontinuity (~70 km). Given the strong evidence that the G discontinuity approximates the lithosphere-asthenosphere boundary beneath ocean basins, we conclude that the upper, weakest part of the oceanic asthenosphere, participates in the cooling that forms the kinematic plates. We do not discount the possibility that small-scale convection creates heterogeneities in the oceanic upper mantle; however, the large-scale flow evidently advects these small-scale heterogeneities along with the plates, allowing the upper part of the asthenosphere to continue cooling with lithospheric age. The dominance of this large-scale horizontal flow may be related to the high stresses associated with channelization in a thin (~100 km) asthenosphere, as well as focusing of the subtectospheric strain in a low-viscosity channel immediately above the 410-km discontinuity.

Icequakes Triggered by Surface Waves From Large Teleseismic Earthquakes

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Passing seismic waves from distant, large earthquakes are known to nearly instantaneously trigger shallow microearthquakes and deep tectonic tremor. Remotely triggered seismic activity has been predominantly reported in tectonically active regions, and is generally attributed to shear failure on critically stressed fault planes. Here we note the discovery of a new kind of high-frequency cryoseismic event that is triggered by teleseismic surface waves. In this case we examine small icequakes in Antarctica triggered by the 2010 Mw 8.8 Maule, Chile earthquake. Unlike shear sources observed elsewhere that are triggered by both Love and Rayleigh surface waves, these events are principally associated with Rayleigh waves. Locations are difficult to ascertain due to sparse network coverage and small event size, but some triggered signals are dispersive and have large Rayleigh wave components, and hence are likely associated with near-surface sources producing appreciable short period surface wave energy. Although we cannot constrain source mechanisms, the observations are consistent with tensile or other fracturing of near-surface ice as a result of volumetric strain changes incurred during the passage of high-amplitude Rayleigh waves. We are in the process of searching for similar evidence of triggered icequakes in other regions. Further study of this phenomenon may yield information regarding the critical stress state of some dynamic glacier features.

Observations of Seismic Whistlers in USArray

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Unusual seismic signals in several Transportable Array (TA) stations in the Central US are observed. These signals bear a superficial resemblance to downward-sweeping VLF electromagnetic waves spawned by lightning called "whistlers." Although not likely related to their electromagnetic cousins, these "seismic whistlers" are primarily seen in two distinct categories: low frequency and high frequency. Low frequency seismic whistlers are typically seen from 3 to 7 Hz over a period of about five minutes and show a multi harmonic downsweeping signal followed 12 to 15 minutes thereafter by an upsweeping signal with similar harmonics. These coincide with long periods (tens of minutes to over an hour) of continuous low-frequency signal with multiple harmonics. The continuity of this signal over time is suggestive of a nearby man-made source. High frequency seismic whistlers are rarer, however, and they are typically observed in a frequency band from 20 to 15 Hz over a time period of one or two minutes. Like electromagnetic whistlers, these consist of a single downsweeping harmonic. Though the source of these signals is unknown, we attempt to determine when and where these signals are observed in the seismic data and, when available, barometric and infrasound data. Because strong seismic whistler signals were seen prior to the May 22, 2011 EF-5 Joplin tornado, we also investigate whether there is a link with other storm systems near TA sites. Audio renditions of the data were used to help identify seismic whistlers and will be available at the presentation.

Permeability Evaluation According to Complex Precision Observations

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Recently, in seismically active regions researchers focus on the analysis of the influence of external and internal factors on the stress-strain state of massif. In particular, the recorded data of the earth tides in seismic and hydrogeological series are used to estimate reservoir permeability that may change due to earthquakes. Tidal components subjects to the annual periodicity. For semidiurnal waves maximum values of the ground velocity and underground water level are traced in March and September and minimum values – in June and December.

Simultaneous observations of the underground water level in the well and microseismic noise have been carried out for the last six years at the territory of the geophysical observatory of the Institute of Geosphere Dynamics. Application of an original technique allowed to determine the range of annual variations of the semidiurnal and diurnal tidal components in the ground displacement and underground water level, to estimate the amplitude factor and phase shift. The obtained data are used to evaluate the reservoir permeability of fractured-porous type with account for peculiar properties of the formation of hydrogeological environment.

To extract the informative intervals associated with a downward and restore the piezometric surface pre-filtering hydrogeological data on the influence of atmospheric pressure was performed. For each interval phase portrait between the ground displacement and underground water level was considered. It was found that the range of variations of the phase shift is changed every year from 5 to 14 degrees. It should be noted that intervals with increase of the groundwater level correspond to the lower values of phase shift as compared with segments with water level drop at the same values of filtration velocity.

Topics in Seismology: Regional Seismicity and Tectonics

Poster Session · Thursday · 1 May · Cook/Arteaga

Properties of the Subduction System in Mexico

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We exploit dense seismic data (MASE, 2007; VEOX, 2010) to better define the subduction structure beneath Mexico. Our images provide insight into the process of subducting relatively young oceanic lithosphere and its complex geometry beneath continental North America. The converted and reverberated phase image for central Mexico shows complete horizontal tectonic underplating of the Cocos plate beneath the North American plate, with a clear image of a thin low-velocity oceanic crust which dips at 15–20 degrees at Acapulco then flattens to approximately 300 km from the trench. A low-pressure mineral phase such as talc is considered a prime candidate for anomalously low shear speeds at the subducted (top) interface of the Cocos plate. The evolution of this low-strength zone has important implications for the dynamics of the slab-flattening process as well as the geochemistry of the mantle wedge and arc in central Mexico.

In southern Mexico, there are several unusual surficial features that cannot be explained by the subduction of the Cocos plate and low-relief relic fracture zone known as the Tehuantepec Ridge. The dip of the Cocos plate is ~25 degrees based on converted analysis, and the signature of the oceanic crust is absent beyond the depth of ~150 km. Our seismic images on the Isthmus of Tehuantepec show an enigmatic seismic structure dipping south from the Gulf of Mexico. The images argue that this structure represent a slab although standard models of Caribbean tectonics do not support this observation.

The Significance of the Yakutat Plate to the Alaska Orocline

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The arcuate structures of major Alaskan faults such as the Denali are the bases of Carey's (1955) Alaska Orocline, which has attracted numerous models such as rotation of blocks about a point (Coe, 1989; Plafker & Lahr, 1980; St. Amand, 1957), the nonrigid world of escape tectonics (Redfield et al., 2007) & finite element diffusion (Finzel et al., 2011), and the multiple bending of rigid layers like Grantz's (1966) megakinks or multiple thrust bending like Glen's (2004) conveyor belts. But, for all, the expected extensional and compressional structures on appropriate arc sides (Schultz & Aydin, 1990) and rotated and/or arched structures (Csejtey, 1990) are mainly lacking. None explain the existence of the Copper River, Nenana and Tanana basins. Another serious problem is the large offset disparities between E and W of the curved fault systems (Lanphere, 1978; Miller et al., 2002). Why all of these problems? It has been the lack of proper accounting for the subduction of the Yakutat Plate into the Katmai, Cook Inlet, and Mount McKinley parts of the Aleutian subduction zone. The Freymueller et al. (2008) 'Southern Alaska Rotating Block' should be replaced with the Yakutat Plate. This Plate would have a boundary with the Bering Block at the Aleutian subduction zone. The Yakutat Plate is pulling away from the Wrangell volcanic arc and Copper River basin as a spreading ridge into the Cook Inlet part of the Aleutian subduction zone, with the Pacific Plate still causing a Wrangell subduction zone (Stephens et al., 1984). The Totschunda and Fairweather faults are the new westward developing Denali transform. The Nenana and Tanana basins formed earlier in a similar fashion to how the Copper River basin is now forming. The Yakutat Plate is forming at the expense of the Pacific Plate and it is transporting mass WSW along its own transforms into the Aleutian subduction; creating a more 'steady state' Alaska Orocline!

Seismicity in the Basin and Range Province of Sonora, México, near the Rupture of the 3 May 1887 Mw 7.5 Earthquake, between 2003 and 2011

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We studied the regional seismicity in the Basin and Range Province of Sonora, México near the epicentral region of the 3 May 1887 Mw 7.5 earthquake. We used body wave arrival times recorded by the local network RESNES (Red Sísmica del Noreste de Sonora) and two regional broadband stations of the RESBAN (Red Sismolígica de Banda Ancha del Golfo de California) network to locate the seismic sources originating between 2008 and 2011. We first determined preliminary hypocenter coordinates with the program Hypoinverse (Klein, 2002) and then relocated the initial coordinates with the source-specific station term method (Lin and Shearer, 2005). We had used the same procedure in a previous study (Castro et al., 2010) to locate the earthquakes originating in the same region between 2003 and 2007. We also present in this paper a depurated catalog of events recorded from 2003 to 2011. Most relocated events cluster near the faults that ruptured during the 1887 earthquake. Additionally, we document seismicity along Basin and Range Province normal faults south of the 1887 rupture, such as the Villa Hidalgo and Granados faults and the faults bounding the Bacadéhuachi basin. The region of the largest population center, Hermosillo, appears to be seismically quiescent. This observation is supported by a lack of entries in the catalog of the International Seismological Centre (ISC) or documented historical seismicity in that area.

Seismic Studies of the Jalisco Block

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Many societies and their economies endure the disastrous consequences of destructive earthquakes. The Jalisco region at Mexico is exposing to this natural hazard. Scientific knowledge constitutes the only way to avoid or at least to mitigate the negative effects of such events. Accordingly the study of geological and geophysical causes; structural, kinematics and dynamic characteristics; and destructive effects of such events are indispensable. Seismology constitutes a very important tool to study the structure as well as the earthquakes within the area; in this way we are analyzing different data sets. We use seismic data recorded from 2006 to 2008 by the Mapping the Riviera Subduction Zone (MARS) and the Colima Volcano Deep Seismic Experiment (CODEX) deployed in western Mexico. Additionally, we are analyzing data continually recorded by the Jalisco Seismic Network (RESAJ). We are also deploying another seismic experiment to characterize the seismic and tsunamic risk associated to the Rivera Plate and Jalisco Block structure (TSUJAL). We present a description of these seismic experiment as well as preliminary results that include seismicity maps, local and teleseismic tomography as well as an analysis of this result and the plan for future research.

Revisiting the Uljin Sequence of April 2006

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An earthquake sequence comprised of 10 reported events from the Korea Institute of Geoscience and Mineral Resources (KIGAM) catalog occurred in April of 2006. The sequence was located off of the eastern coast of the Southern Korean peninsula in the northwest corner of the Ulleung Basin. Due to the lack of a typical mainshock-aftershock sequence the seismicity is characterized as swarm behavior with magnitudes determined by KIGAM as ranging from M_L 2.0 to 3.2 (Kang and Shin, 2006). Observations from regional seismic data show that these events are highly correlated. We employ a pseudo array correlation technique to detect an additional 4 events not previously associated to the sequence. Further, we perform relative relocations of the sequence's events. This is accomplished by picking the phase arrivals manually by aligning waveforms of the events at common stations. The relative locations delineate two distinct parallel segments from SW to NE. This result supports assertions regarding the fault geometry in the northwest Ulleung Basin by previous researchers [Kang and Baag, 2004; Kang and Shin, 2006].

Analysis on Co-seismic Responses of Well Water Level and Water Temperature in Ganshu Province to Wenchuan Ms8.0 Earthquake and Japan Ms9.0 Earthquake

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The two earthquakes of Wenchuan (8.0) occurred in May 12, 2008 and Japan (9.0) occurred in March 11, 2011 have significantly impacted on Chinese underground fluid. An important example is the well water level and well water temperature in Gansu province recorded the change during two earthquakes. The distance between Wenchuan and Gansu is short, which is about hundreds kilometers. However, Japan is far from Gansu. It provided a good condition to study the response characteristics of well water level and temperature in short and long epicentral distance. All the observations of well water level and temperature recorded obvious coseismic changes during Wenchuan earthquake. There were only five obvious records of well water level with Japan earthquake and the well water temperature did not record apparent changes.

Comparative study find that there are many obvious differences of characteristics coseismic effects of well water level stations and well water temperature, which caused by Wenchuan Ms8.0 earthquake in 2008 and in 2009. The majority of well water level and well water temperature records the coseismic effect after Wenchuan earthquake, moreover, the magnitude is large and the duration is long. On the contrary, only a little well water records the coseismic change after Japan earthquake, which is effected by the epicentral distance and focal orientation, Although the energy is even more released from Japan earthquake. There is obvious coseismic change in the well water temperature after Japan earthquake. Well water level in Gulang station records the change after the two earthquakes, however, the variation after Japan earthquake than after Wenchuan Earthquake, which is worthy of further study.

Seismicity of the Lau Basin as Viewed from Ocean-Bottom Seismometer and Sound Channel Moored Hydrophone Arrays

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Local seismicity within the Lau back-arc basin has been studied using two complimentary technologies. Between January 2009 and April 2010, a broad region centered on the Eastern Lau Spreading Center (ELSC) was monitored using a network of five to six sound-channel-moored hydrophone stations to detect earthquake-generated T-waves and volcano-acoustic signals. In total, more than

60,000 seismo-acoustic origins have been detected using the hydroacoustic dataset. Most occur outside of the array, and can be associated with submarine volcanoes within the Tofua Arc. Between November 2009 and November 2010, fifty-one broadband three-component ocean bottom seismometers (OBS) were deployed within a smaller-aperture array along the central portion of the ELSC. More than 9,000 microearthquakes were located in the vicinity of the ELSC using the OBS array. Where the two datasets overlap, a similar picture of back-arc seismic activity emerges. Earthquakes are clustered near overlapping spreading centers along the ELSC and within a few short-duration swarms positioned along the spreading axis (near 19.92S, 20.87S and 21.15S latitude). Larger earthquake swarms are concentrated off axis on the eastern flank of the spreading center. The most persistent cluster of off-axis activity is sustained for several months and associated with a group of volcanic cones located approximately halfway between the ELSC and the active Tofua volcanic arc (20.58S, 175.98W). We interpret this activity to track active seamount formation within the Tonga Plate.

Downhole Seismic Monitoring in the Istanbul/Eastern Sea of Marmara Region: Recent Results from the ICDP-GONAF Project

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The North Anatolian Fault Zone (NAFZ) below the Sea of Marmara represents a 'seismic gap' where a major earthquake is expected to occur in the near future. The Marmara segment of the NAFZ is located between the 1912 Ganos and 1999 Izmit ruptures and is the only segment that has not ruptured since 1766. The ICDP-GONAF project (Geophysical Observatory at the North Anatolian Fault; www.gonaf.de) involves the installation of a high-resolution borehole seismic observatory at the NAFZ consisting of several 300m deep vertical boreholes in the broader Istanbul / eastern Sea of Marmara region to monitor the Princes Islands segment at the transition from the 'seismic gap' to the recent 1999 Izmit rupture. GONAF is an international collaboration and co-funded by the International Continental Scientific Drilling Programme (ICDP), GFZ Potsdam and the Disaster and Emergency Management Presidency in Ankara/Turkey (AFAD). Further principal partners are IESE/New Zealand, JAMSTEC/Japan, MIT and UNAVCO/both US,. The principal scientific objective of GONAF is to study physical processes acting before, during and after the expected M>7 earthquake along the Princes Islands segment by long-term monitoring microseismic activity at significantly reduced magnitude detection threshold and improved hypocentral resolution. By the end of 2013 three GONAF boreholes were successfully implemented and arrays of borehole seismometers were installed for permanent operation. Vertical 1Hz seismometers at 75m spacing as well as several different 3-component borehole seismometers at 300m depth are installed and are completed by a set of surface sensors. The benefit of seismic waveforms recorded at depth in a low-noise environment is shown and first results of microseismic activity along the Princes Islands segment are presented and will be discussed in the seismotectonic context.

An M 4.8 Earthquake in the Upper Mantle Beneath the Wind River Range, Wyoming

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On Sept. 21, 2013, a rare continental-interior upper mantle earthquake of M_W 4.8 occurred beneath the Wind River Range of western Wyoming at a depth of 70–85 km below the surface. This depth is well within the upper mantle, based on published estimates of crustal thickness near the epicenter (43.0 N, 109.1 W) which range from 40–50 km. Moment tensor inversions indicate strike-slip faulting with a small reverse component, either left-lateral on an ENE-striking plane or right-lateral on a NW-striking plane. The only aftershock detected was an M_L 2.8 event 2 hrs after the mainshock. An empirical Green's function analysis using mainshock and aftershock records shows an apparent source duration for the mainshock of 0.52 s with minimal azimuthal variation. Application of a circular source model gives a source radius of 0.9 km and a stress drop of 100–130 bars.

The evidence for the depth of the Wind River earthquake includes: (1) four moment tensor inversions of long-period waveforms; (2) a regional network location determined with 59 P and S arrival times from stations at epicentral distances of 45–460 km, with one at a distance of less than one focal depth; (3) a global network location with 458 phase arrival times from stations between 0.4 and 148 deg, including 78 pP and sP times; and (4) an apparent P-wave velocity of 12.6 km/s observed on the 13-element Pinedale array, centered ~50 km SW of the epicenter. The earthquake occurred on the NW edge of the Wyoming craton, a high velocity anomaly in the upper mantle located SE of the low upper mantle velocities along the Yellowstone hot spot track. Another upper mantle earthquake (M_L 3.8) occurred on the W edge of this anomaly in 1979 at a depth of 80–90 km as reported by Zandt and Richins (1979). We suggest that both events might be related to stresses, thermal gradients, and/or fluid flow associated with interactions between the Yellowstone hot spot and the Wyoming craton.

Implications of Gravitational Anomalies within the Muckleshoot Basin of Northwest Washington

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This study presents a preliminary model based on new and existing gravity and magnetic data for the Muckleshoot basin near the Puget Sound, Washington. The principle goals of the project are to determine whether and how faults mapped outside of these basins continue beneath their thick sedimentary cover. Magnetic data and new gravity data support the existence of at least two subbasins within the Muckleshoot that are likely separated by a fault. Cross-sectional models focus on the possible connection of the east-trending Seattle fault (northwest of the basin) and the northwest-trending White River fault, mapped to the east of the Muckleshoot basin. Gravity and magnetic maps show the trajectory of the White River fault aligning with anomaly lineations that separate the basin and the known location of the Seattle fault. A connection between these two fault systems would have significant implications for hazard estimates in terms of the length and size of these seismogenic structures and the maximum magnitudes that could be generated by faulting.

Delineation Seismic Source Zones Based on Seismicity Parameters and Seismotectonic Characteristics Around Sabah and North Borneo

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The delineation of seismic source zones plays an important role before the analysis on seismic hazard is done. The seismic source delineation based on the description of the various tectonic and geological features with the association of historical seismicity was performed to delineate seismic source zones around Sabah, North Borneo. Sabah is located at the triple junction of the Pacific (through the Philippine plate), Indo-Australian and Eurasian Plates with the rate of spreading 100 mm, 110 mm and 40 mm per year respectively. The interactions among the plates are very complex and active. Sabah situated at the location of being affected by low seismic active level from the Sunda tectonic plate and moderately active seismic level from Kalimantan and Sulawesi. Moreover, the state also have experienced earthquakes of local origin with low-to-moderate earthquakes are frequently known to have occurred in most cases and achieved to the level of VIII from MMI scale. The local earthquake of Sabah concentrated in three areas known to Central North Zone, Labuk Bay Sandakan Zone and Dent-Semporna Peninsular Zone. In regional aspect, the tectonic features that affected Sabah can be divided into three classifications, i.e. subduction zone, transform zone and background seismicity zone with total of 12 seismic sources. The b-value parameter is computed in each source and was estimated to be 0.284 to 1.442. Furthermore, probabilistic seismic hazard analysis has been carried out and the highest estimated values of peak ground acceleration (PGA) at rock level are approaching above 250 gals for 10% probability and above 400 gals for 2% probability in a life span of 50 years corresponding to a return period of 500 and 2500 years, respectively. These values are much higher than previous PGA values of 150 gals and 250 gals, respectively, which maybe due to the new Sulu Faults lines now found near Sabah.

From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering

Oral Session · Friday · 8:30 AM · 2 May · Room 1 Session
Chairs: Luis A. Dalguer, Carlo Cauzzi, Aysegul Askan and Philippe Gueguen

Does a 1D Velocity Structure Hurt or Help Ground Motion Predictions?

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For linear response, ground motion is a convolution between the source and Green's functions (GFs) for an anelastic structure. While 1D anelastic structures may provide a template to compute arrival times (high frequency), GFs (for these layered structures) convolved with the source can naturally underestimate the ground motion amplitude at high frequencies. With source being embedded in the mostly homogeneous structure, the up-going rays from the fault impinge with a large incidence angle the bottom of the near-surface layers and glance off. The low-frequency ground motion is also affected. The near-surface layering leads to natural waveguides for surface waves that tend to be larger than those observed for most earthquakes, thus overestimating response spectra at high periods. The fundamental erroneous assumption in using a 1D structure is that the uniform layers exist over a wide range of distances. Some boundaries, e.g., the Moho, obviously persist over large distances. But the assumption that near-surface uniform layers that are 10's of m thick exist over 10's of km, is certainly false. Imperatori & Mai (2013) incorporated randomness into a 3D velocity structure; the randomness leads to 50–60% attenuation in PGA and 20–30% attenuation in PGV even at distances less than 20 km. While this approach is a laudable, it is currently impractical (numerically expensive) for large distances. Recent results (Dunham et al., 2011; Fang & Dunham, 2013; Shi & Day, 2013) demonstrate that fault roughness leads to a random wavefield. The UCSB method (Liu et al., 2006; Schmedes et al., 2013) embeds randomness into the source by the choice of distribution functions for the kinematic parameters. Since ground motion is a convolution of source and path, we propose using randomness in the source convolved with a nearly homogeneous anelastic structure. We compare synthetics with response spectra based on ground motion prediction equations for the western US (Earthquake Spectra, 2008).

Stress Drop Variations and their Relevance for Ground Motion Prediction

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Stress drop is one of the key parameters characterizing the earthquake source process and therefore also a fundamental input parameter for ground motion prediction. However, at the same time, stress drop is difficult to accurately determine. Stress drop estimates are commonly derived from corner frequencies of earthquake source spectra, and these estimates carry large uncertainties because stress drop depends on corner frequency cubed. Large earthquake populations usually show stress drop variations as large as three orders of magnitude. Assuming such a large range of stress drop variations leads to very large ground motion variability solely as a result of the source process, notwithstanding any variability due to propagation and site effects. On the other hand, it has recently been shown that the between-event variability obtained from ground motion prediction equations (GMPEs) implies significantly smaller variability in earthquake stress drop than source spectral studies generally do.

In order to get new insights into the potential reasons for these contrasting findings, we present a dataset encompassing earthquakes of a wide magnitude range and spatial coverage in Japan for which corner-frequency based stress drops have been determined. These stress drop estimates show systematic lateral variations. Accounting for these systematic variations reduces the stress drop variability on local scale by a factor of two to three as compared with the full earthquake population, which is closer to the stress drop variability estimates obtained from GMPEs. The between-event terms obtained from regression analysis of the same dataset used for the source spectral study will be discussed in this context.

Stress Drop Variability and its Relationship to Variability in GMPEs

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Earthquake stress drop is an important predictive parameter in ground motion estimation and should correspond to the short-period event residual from a ground motion prediction equation (GMPE). The overall variability of seismologically estimated stress drops, however, is much larger than tau, the standard deviation of the event residuals from the GMPEs for peak ground acceleration (PGA). Using the NGA-West2 data base and KikNet data from Japan, we investigate the source of this discrepancy, employing several metrics for stress drop: the traditional Brune stress drop, dependent on moment and corner frequency cubed; the aRMS-stress drop of Hanks [1979], dependent on the moment and the square root of the corner frequency; and the stress parameter from Boore [1983]. The stress parameter is akin to a PGA-determined stress drop, estimated from the peak ground acceleration (PGA) of an event and the earthquake moment, which can also be modeled through stochastic ground motion simulations. We find that the reduced variability seen in the PGA event terms from GMPEs is attributable to several factors, including excellent data quality and processing in the NGA database; reduced natural variability of PGA measurements as opposed to spectral determination; and error propagation when calculating a Brune stress drop, due to the cube of the corner frequency. In addition, the NGA-West2 2014 GMPEs (e.g., Abrahamson, Silva and Kamai, 2014) consider mainshocks and aftershocks separately, finding a decrease in PGA amplitudes by 0.3 ln units for Class 2 events, on-fault aftershocks, as compared to the Class 1, stand alone events. Using the same classification, we find a similarly smaller stress parameter for the Class 2 aftershock events by ~30%. A lower stress drop for on-fault aftershocks may imply that they are re-rupturing damaged zones or weak asperities. Incorporating this difference when considering the variability of stress drop and of GMPEs is important.

Identification of Near-Field Ground-Motion Characteristics and Predictors Based on Synthetic Data Obtained from Dynamic Rupture Models

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Proper characterization of ground motion parameters is a fundamental input to structural design, seismic vulnerability, hazard and risk assessment studies. Although empirical ground motion prediction equations (GMPEs) are extremely useful for these purposes and routinely used in engineering seismology and structural earthquake engineering applications, current models still suffer from some paucity of recorded data in the near-field region of potentially damaging earthquakes. Therefore these GMPEs are insufficient for the prediction in the near field because they do not adequately quantify potential source effects. A way to cope this shortcoming is using synthetic ground motion data to develop hybrid-GMPEs. Dynamic rupture models appear to be a very strong candidate to produce such synthetic ground motions, as these models have the potential to identify source-dominated shaking phenomena. In this direction, we first perform an assessment of a database of synthetic ground motions generated by a suite of dynamic rupture simulations to verify compatibility of the peak ground amplitudes with current GMPEs. Second, we parameterize the synthetic dataset through a synthetic GMPE oriented to the implementation of a hybrid-GMPE that account for the above mentioned source effects in the near field. Particular emphasis is placed on the supersaturation (ground motion reduction) in the very-near field identified by our numerical simulations (Baumann and Dalguer, 2014) and suggested by some observation of real earthquakes (e.g. Akkar and Bommer, 2007, Graizar and Kalkan, 2007, 2011). Our dataset show that this supersaturation, generally not modeled in empirical GMPEs, is particularly pronounced in strike-slip buried rupture scenarios. An adequate quantification of this phenomenon and its uncertainty may have significant implications on earthquake hazard and risk assessment models based on standard approaches.

Squeezing Kappa out of the Transportable Array: When the Going gets Tough

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The high-frequency attenuation parameter (Anderson and Hough, 1984), and, in particular, its site-specific component (κ_0) is an important input parameter for ground motion prediction and simulations. The frequencies it controls (above 10–20 Hz) are important to the seismic response of safety-related equipment in nuclear facilities. We present a case where the seismicity and instrument characteristics render its measurement a challenge. Our site is located in a low seismicity region (S. Arizona). The available seismic records are few and often noisy.

They are at distances between 10–300 km, which makes the trade-off between site and path attenuation significant. The event magnitudes (M1.2-M3.4) are rather low for the classic κ estimation method to be used. The stress drop values from different studies in the region vary greatly (1–50 bar), leading to large uncertainty in the source corner frequencies. Hence κ should be measured ideally above 10 Hz (above M3) or 20 Hz (below M2) to avoid trade-offs. Possible high-frequency resonances due to shallow soil layers may also interfere with the measurement. However, because our data comes from the Transportable Array, the low sampling rate limits the maximum usable frequency to 16 Hz. This allows us very little bandwidth to resolve source, path, and site effects and constrain κ_0. We use three measurement approaches (above the corner frequency, below it, and across the entire frequency range) to define upper and lower bounds for κ_0 in S. Arizona, as well as estimates of regional Q and stress drop. The TA has greatly increased the available dataset for North America and, in certain low-seismicity regions, represents the majority of available seismic records at short distances. The severe obstacles faced in this study will be relevant in future κ studies in other regions with such band-limited data. We believe that an increase in the sampling rate of the TA would help avoid them.

Progress of the Southern California Earthquake Center Technical Activity Group on Ground Motion Simulation Validation

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Strong ground motion records are fundamental to engineering applications such as nonlinear response history analysis of geotechnical or structural systems for building code or risk assessments, and the development of prediction models for ground motion intensity measures. Although thousands of strong motion records are available today, there is a shortage of records for large-magnitude earthquakes at short distances, as well as records that sample specific combinations of source, path, and site characteristics. Owing to the development of numerical source-excitation and wave-propagation codes, deterministic and stochastic simulation methods now offer increasingly realistic models of strong ground motions. However, in order to be useful in engineering applications, simulated records must first be statistically validated against available data. The development and implementation of validation methodologies requires collaboration between ground motion modelers and engineering users. To facilitate this, the Southern California Earthquake Center (SCEC) maintains a Technical Activity Group (TAG) focused on Ground Motion Simulation Validation (GMSV). Since April of 2013, the GMSV TAG has made progress on the GMSV-related SCEC projects funded in 2013, and on validation efforts within the Software Environment for Integrated Seismic Modeling (SEISM) project. The SEISM efforts are focused on validation in terms of engineering metrics like nonlinear building response and seismic slope stability, in contrast to the Broadband Platform Validation project, which is focused on validation in terms of elastic spectral acceleration. At two 2013 workshops, plans for future GMSV projects, such as validation of simulation-based probabilistic seismic hazard analyses that will support the SCEC Committee for Utilization of Ground Motion Simulations (UGMS), were also discussed. In this presentation, given on behalf of the SCEC GMSV TAG, we summarize this progress and outline future plans.

Stochastic Model for the Simulation of Seismic Ground Motion for Reliability Analysis of Industrial Structures and Components.

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The simulation of synthetic accelerograms by means of stochastic ground motion models is very popular in the engineering community. This is mainly due the simplicity and computational efficiency of this approach. Once established, the stochastic model allows to simulate an unlimited number of time history at negligible cost and thus to perform advanced structural reliability analysis and risk assessment. In the stochastic approach, seismic ground motion is modeled as a stochastic, most often Gaussian, process characterized by its power spectral density. The concept of evolutionary power spectral density (Priestley 1985), allows, in a statistical way, to account for the time dependent features linked to the arrival times of different wave types (body and surface waves). Moreover, directivity effects can be readily introduced by adding velocity pulses according to their statistical distribution (Mavroeidis & Papageorgiou 2003, Baker 2006) to the simulated time histories. The use of a spatial coherency function allows to model and simulate a vector valued process and thus to account for the spatial variability of ground motion. Stochastic models are thus very versatile. But seismological data and models are needed to feed these parameterized models in order to make them physically sound. Furthermore, being artificial accelerograms, the question of representativeness of real events arises.

This contribution proposes to discuss some popular stochastic ground motion models available in literature. Then, the stochastic ground motion model developed at EDF R&D, available through Code-Aster finite element software, is presented. Special attention will be drawn to verification and validation with respect to seismological models and data. An application to the computation of fragility curves illustrates the purpose.

Directivity Pulse Characterization of NGA-West2 Earthquakes – PSHA Implementation and Seismic Structural Response Implications

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The need to directly account for directivity effects in seismic hazard analysis models has long been recognized by earthquake seismologists. In particular, characterizing directivity pulses in future earthquakes for seismic response analysis of structures has been the subject of many recent investigations. One current practice in seismic design for directivity is to use wavelet analysis on fault-normal components of velocity time histories of selected records within 20 km or less of the source to extract a single pulse. The pulse is then attributed to rupture directivity assuming certain conditions are met. In regard to identification and use of directivity pulses, there are many issues needing further studies. These include the use of earthquake-specific versus record-specific pulses, acceleration pulse versus velocity pulse, multiple pulses versus single pulse, fault-parallel versus fault-normal pulse, and conditions beyond 10-20 km.

As part of the NGA-West2 project, the author developed a directivity model based on which directivity effects at a site is quantified using a single parameter defined by the directions of rupture and slip. This model was used to study some of the afore-mentioned issues on pulse characteristics. Analysis for earthquakes in the NGA-West2 database, using ground motion residuals of NGA-West2 GMPEs, resulted in multiple periods of strong directivity (i.e., multiple pulses) for most earthquakes studied. The study identified factors which control the characteristics of the pulses, that is, number of pulses in each earthquake, pulse periods, and strength of individual pulses in the group. These include proximity to the source, faulting mechanism, heterogeneity of rupture, and directionality of ground motions. Some of the findings of the study will be presented. One significant conclusion is that use of a single velocity pulse (based on very-near-source fault-normal ground motion components) could lead to incorrect estimation of seismic demand.

Ground Motions Due to Earthquakes on Creeping Faults

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We investigate the peak ground motions from the largest well-recorded earthquakes on creeping strike-slip faults in active-tectonic continental regions. Our goal is to evaluate if the strong ground motions from earthquakes on creeping faults are smaller than the strong ground motions from earthquakes on locked faults. Smaller ground motions might be expected from earthquakes on creeping faults if the fault sections that strongly radiate energy are surrounded by patches of fault that predominantly absorb energy. For our study we used the ground motion data available in the PEER NGA-West2 database, and the ground motion prediction equations that were developed from the PEER NGA-West2 dataset. We analyzed data for the six largest well-recorded creeping-fault earthquakes, that ranged in magnitude from M5.7–6.5. These are the 1966 and 2004 Parkfield, 1979 Imperial Valley, 1979 Coyote Lake, 1984 Morgan Hill, and 1987 Superstition Hills events. Our findings are that these earthquakes produced peak ground motions that are statistically indistinguishable from the peak ground motions produced by similar-magnitude earthquakes on locked faults. These findings may be implemented in earthquake hazard estimates for moderate-size earthquakes in creeping-fault regions. Further investigation is necessary to determine if this result will also apply to larger earthquakes on creeping faults.

A Naive Bayesian Approach to Strong Ground Motionn Selection for Non-Linear Seismic Analysis of Structures

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In this work, we investigate the possible role of ground motion intensity measures (IM) in constraining data selection. To this aim, we propose a naive Bayesian inference scheme to predict the response of a single degree of freedom (SDOF) system in function of a set of IM.

We modeled 6 non-linear SDOF systems with initial fundamental frequency of 1, 2 and 5 Hz and with different strength reduction factors. The Takeda hysteretic model describing the structural behavior and the structural demand is expressed in terms of relative drift. A database of 6373 strong motion records was built from

worldwide catalogues and has been described by a set of 'classical' IM. The SDOF response is reduced in a description of three possible statuses: elastic, if the induced drift is lower than the yield displacement, plastic if the drift ranges between the yield and the ultimate drift values and fragile if the drift reaches the ultimate drift. Our goal is to evaluate the conditional probability of observing a given status of the SDOF system in function of the IM array. The results of the Bayes classification on the training dataset are quite promising. Indeed, to validate the presented methodology and evaluate its prediction capability, we performed a blind test on a second dataset, completely disjointed from the training one, composed of 7000 Japanese waveforms. We classified Japanese data using the probability distribution functions issued on the first data set. The results on Japanese dataset are encouraging; however the critical point is the discrimination between the waveforms pushing the SDOF system in plastic state and those inducing a fragile behaviour. To better understand what are the seismic features related with the plastic and fragile behaviour, we will perform a time-frequency analysis using the Stockwell transform. This latter part of the work is devoted to interpret the Takeda behaviour making a link between the engineering and seismological features.

On the Use of Earthquake Early Warning and Operational Earthquake Forecasting for Real-Time Risk Mitigation at Nuclear Power Plants in Switzerland.

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Selectively presented in this contribution are the main activities carried out and results obtained within a research initiative devoted to a feasibility study and initial implementation efforts of Earthquake Early Warning (EEW) and time-dependent seismic hazard analyses aimed at mitigating seismic risk at nuclear power plants (NPP) in Switzerland. This research task is being carried out within the EC-funded project REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction, FP7, contract no. 282862, 2011–2014, www.reaktproject.eu), and involves academic institutions (SED at ETHZ and BRGM) and swissnuclear, that operates 4 nuclear power plants in Switzerland providing ~ 40% of the electricity needs of the country. The study comprises: a) assessing the performances of the selected EEW algorithm – the Virtual Seismologist, VS (Cua, 2005; Cua and Heaton, 2007; Cua et al., 2009) – in Switzerland and California, in terms of correct detections, false alerts, and missed events; b) embedding the VS algorithm into the earthquake monitoring software SeisComP3 (www.seiscomp3.org, Behr et al., 2013) routinely used by the SED at ETHZ; c) customising the Caltech User Display to ensure optimised use at swissnuclear, by means of developing and implementing Swiss specific ground-motion prediction tools (Edwards and FAh, 2013; Cauzzi et al., 2013) at the target sites; d) compiling synthetic time-dependent hazard scenarios for Switzerland and e) combining the above input data into a cost-benefit analysis on the use EEW and operational earthquake forecasting (OEF) as real-time earthquake risk mitigation tools for NPP in Switzerland.

Real-time GPS enhanced Earthquake Early Warning: The Northern California Setup

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In an effort to improve earthquake parameter estimation in earthquake early warning (EEW) for large earthquakes (e.g. Mw, finite fault geometry), the Berkeley Seismological Laboratory (BSL) works on integrating real-time GPS into EEW, and generates and archives real-time position estimates using data from 62 GPS stations in the greater San Francisco Bay Area. This includes 26 stations that are operated by the BSL as part of the Bay Area Regional Deformation (BARD) network, 8 operated by the USGS, and 29 stations operated by the Plate Boundary Observatory. We set up a fully triangulated network scheme in which neighboring station pairs are processed with the software trackRT. Positioning time series are produced operationally for about 170 station pairs; additional station pairs will be added as more real-time stations become available.

G-larmS, the geodetic alarm system, sits on top of real-time GPS processors (e.g., trackRT) and analyzes real-time positioning time series, and determines and broadcasts static offsets and quality parameters from these. Following this, G-larmS derives fault and magnitude information from the static offsets and broadcasts these results as well. This Python implementation is integrated into seismic alarm systems (CISN ShakeAlert, ElarmS) as it uses their P-wave detection alarms to trigger its processing.

The BSL now runs G-larmS in real-time test-mode for Northern California. Here, we present the setup and report results of the first months of operation. This includes analysis of system latencies, noise, and response to actual events and results produced by G-larmS. As the BSL generates differential positions over relatively short baselines, we also test how such baseline strains compare to absolute position changes in the case of a very large large earthquake. We perform this analysis on data from the 2011 Mw 9.0 Tohoku-oki earthquake, add randomly selected real-time noise, and invert for slip along the subduction zone interface.

An Evaluation of U.S. Geological Survey's PAGER's Alerting Accuracy

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We review the success rate of USGS's PAGER earthquake impact alerts for events since September 2010. PAGER employs a four-level alert schema of green (little or no impact), yellow (regional impact and response), orange (national-scale impact and response), and red (international response) with corresponding estimated fatality thresholds of 1, 100, and 1000+; commensurate economic loss thresholds are $1 million, $100 million, and $1 billion+. Evaluating alerting success is complicated by several factors: alerts may update once the earthquake source is better constrained, both economic- and fatality-based alerts must be evaluated independently, adjacent alert levels can be nearly equally probable, and the definition of alerting 'success' varies according to the users' perspectives. For example, an updated alert for a small yet deadly earthquake may be released to the majority of users a few hours after origin time (e.g., green alert later raised to yellow), but it may still be very timely for their purposes. We compile a dataset of PAGER alerts as a function of time following each event where economic and/or fatality reports are also available. To quantify alerting accuracy, we compare alerts with corresponding economic and fatality reports for three categories: 1) initial, automatic alerts, 2) updated alerts within eight hours of the event, a selected time period where model-based alerts are still likely to be essential, and 3) final, belated alerts after additional constraints are provided, but beyond the useful time window. Overall, alerts from our initial, automatic results are deemed highly useful, though significant improvements are achieved as revised source parameters and additional data (macroseismic, faulting, strong motion) are added. Such improvements imply that much of the initial errors are often due to uncertainties on the hazard side of the model, though more detailed analyses of individual events indicate loss-model deficiencies in certain cases.

Real-Time Shake Mapping in Istanbul

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The real-time strong ground motion information from the dense Istanbul Earthquake Rapid Response Stations (IERRS) Network has been used in order to generate real-time ShakeMaps for Istanbul City. IERRS Network includes 120 Strong Motion stations located in densely populated areas of the city. The real-time data from each station is transmitted to the main server in Kandilli Observatory and Earthquake Research Institute (KOERI) through 3G. The required parameters such as PGA, PGV and SA(0.2s), SA(1.0) are calculated. The automated input file including related parameters are formed. ELER (Earthquake Loss Estimation Routine) has been utilized in the generation of Shake Maps. ELER provides rapid estimation of earthquake shaking and losses for the target area through its Hazard and Loss modules, respectively.

The ELER – Hazard module basically produces earthquake shake maps using a similar procedure of USGS Shake Map.

The following step by step procedure is used in the estimation of ground motions:

1. Depending on the earthquake epicenter coordination input, the extent of the Shake-Map area drawn.

2. The phantom stations with a user-defined uniform spaced grid are created within the Shake-Map extent.

3. Using the NGA models by taking into account Vs30 value for each grid, the ground motion parameters for each phantom station on the ground surface are calculated.

4. A bias correction is applied to the calculated ground motion parameters by taking into account recorded ground motion parameters.

In addition to the ground motion parameters PGA, PGV, Saa and Sd, ground shaking intensity is also estimated through the regression relationships between MMI and PGA-PGV and regional intensity predictions models.

Multi-Hazard Risk Maps for Coastal Communities of Washington

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Washington State Department of Natural Resources – Division of Geology and Earth Resources (WADNR-DGER) partnered with Federal Emergency Management Agency (FEMA) through the Cooperating Technical Partners (CTP) program to assess annualized losses from flood hazards and prepare inputs for FEMA's coastal Risk Map projects by using HAZUS-MH analysis and assessing/addressing losses from earthquake, flood and other potential hazards such as landslide and tsunami in the project areas. The Multi-Hazard Risk mapping (project) areas are on shorelines of the Pacific Ocean and Puget Sound of Washington: Grays Harbor, Pacific, Skagit, Whatcom, Island, Mason, Clallam, Jefferson and San Juan counties.

HAZUS-MH tool was selected to estimate losses and damages due to flood and earthquake hazards by using updated HAZUS inventory data aggregated using county assessor and Census 2010 information. We built inventory data by using the assessor's data of the counties for risk assessments. We updated general building stocks which are aggregated using Census 2010 blocks/tracts, and generated user-defined data accounting for individual buildings which give better estimates for earthquake and flood risk models.

We then used the updated (Level 2) inventory data as inputs to the HAZUS-MH software to estimate losses and damages for the counties. A likely M9 megathrust cascadia earthquake scenario ShakeMap generated by the USGS was used for the HAZUS-MH earthquake model. HAZUS-MH (earthquake model) results for Grays Harbor and Pacific counties will be presented as examples. GIS maps of properties exposed to tsunami, landslide, and liquefaction hazards within the communities of the two counties will be shown. This multi-hazard risk assessment project that also has an outreach component that will further improve local and regional mitigation and emergency response plans in and around the coastal communities in Washington.

Fatalities in Greek Earthquakes, Past and Future

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There exist reports of fatalities (1 to several thousand) in approximately 100 Greek earthquakes since 464BC. We selected 17 of these for which a magnitude has been estimated, more than 100 fatalities were reported and there was no tsunami. Tsunamogenic events are excluded because we estimate the numbers of fatalities due to damaged buildings, but are unable to estimate flooding effects. Since 1881, there has not been a report of more than 500 fatalities due to an earthquake, thus it appears that Greece has been spared earthquake disasters during the last 140 years, whereas before some large human losses have been reported. We calculated how many fatalities would have to be expected for repeats of the 17 test earthquakes with the tool QLARM and its current model for Greek building properties. Events of $M \geq 7$ were modeled as line sources, smaller ones as point sources. Hypocentral depths were assigned in the top 5 to 20 km, depending on the magnitude and information found in the literature. For one event the depth is given as 90 km. The factors that introduce errors in the comparison include: Inaccurate source parameters, unreliable historical counts of fatalities, unknown deviations from average attenuation properties and local soil conditions, simplification of the QLARM models for population and building stock and unknown time of day for some of the older events. The fact that the QLARM loss calculation comes out within 6 persons of the number reported for the 1999 earthquake near Athens, gives some confidence that our theoretical estimates are meaningful. It turns out that today the numbers of fatalities to be expected are half (median) of those reported historically. Two events deviated from this trend; their estimates for the present were larger than the historically reported numbers. We interpret the overall result as indicating that the improvement of the building stock has reduced the fatality count more than the population growth has increased it.

Macroscale Vulnerability Assessment using Association Rule Learning, a Datamining Tools.

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A complete seismic risk assessment requires not only the estimation of the seismic hazard, but also a representation of the existent buildings quality and expected response through the definition of their vulnerability. The Seismic vulnerability of an urban environment characterizes the capacity of buildings to stand the seismic ground motions. The difficulty in its estimation at the scale of a city is bound to the high amount of buildings to analyse, the construction type variability, the misunderstanding in the behaviour of an old structure, and to the intrinsic variability in the response of structures to seismic loads. The well-known methodologies conceived using post-event damage information in earthquake prone countries cannot be easily applied in moderate-to-low seismic hazard regions like central Europe. We propose a way to perform a fast estimation with a comparable accuracy, using only few, easy-to-get and certain information on buildings. Using a dataset of existing buildings in Grenoble (France) with an EMS98 vulnerability classification and by means of two different datamining techniques Association Rule Learning and Support Vector Machine - we developed a seismic vulnerability proxy. This proxy is applied to the entire country using basic information contained in national databases (census information), obtaining a vulnerability map nation-wide. We also show that including information on building obtained from remote sensing techniques (i.e. treatment of satellite images) we can improve the accuracy on the vulnerability estimation. The approach was validated in Nice (France) by comparison with the RiskUE method and finally, damage estimations were compared with historic earthquakes that produced moderate-to-strong damage in France.

Estimation of Seismic Losses in Urban Regions within an Interdisciplinary Framework: A Case Study

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Risk mitigation in urban regions starts with identification of potential seismic losses in future earthquakes. Estimation of seismic losses concerns a wide range of authorities varying from geophysical and earthquake engineers, physical and economic planners to insurance companies while the process naturally involves inputs from multiple disciplines. In this study we present a city model where potential seismic losses are expressed in terms of building vulnerabilities and regional seismic hazard. The main components of the study are probabilistic and deterministic seismic hazard assessment and estimation of potential ground motions, regional building vulnerability and fragility information, casualty and economic loss functions. As the study area, Erzincan, a city on the eastern part of the North Anatolian Fault zone is selected. Located within a triple conjunction of major fault systems within a basin structure, and experienced a major event (Ms=8.3) in 1939, this city has significant hazard potential. We present the initial results in terms of key components such as construction of a 2D velocity model, ground motion simulations of past earthquakes and scenario events, site-specific probabilistic seismic hazard analyses and fragility functions derived using regional building characteristics along with simulated regional ground motion data.

Evaluation of Building Vulnerability Due to Liquefaction using the Canterbury Earthquake Sequence Observations

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Liquefaction loss models proposed by Hazus (2003) and Bird et al. (2006) account for building damage based on the potential ground surface displacements. Hazus (2003) proposed that cyclic mobility with lateral spreading and cyclic mobility on level ground away from a free-face will create differential building performance. Bird et al. (2006) proposed that tilt, uniform, and differential foundation displacement may be different for various foundation types (stiff/flexible shallow foundation and deep foundations to firm stratum). Both methodologies assume that the free-field ground surface displacement may be used to predict the foundation displacements and recommend liquefaction fragility functions mainly based on engineering judgment. Dashti et al. (2010) proposed that foundation displacements

may not be related to the thickness of the liquefiable deposit in level ground conditions and may not match free-field displacements. This presentation discusses the key dependencies that affect the link between the consequences of liquefaction (ground displacement/liquefied extent) to foundation damage (e.g. tilt, settlement, extension) during the Canterbury earthquake sequence of 2010-2011. A database of liquefaction ground/foundation displacement observations is coupled with the Canterbury Geotechnical Database collected in the Christchurch area to develop preliminary fragility functions. References: [1] FEMA (2003). HAZUS-MH technical manual. Federal Emergency Management Agency, Washington, DC. [2] Bird J. F., Bommer J. J., Crowley, H., Pinho R., (2006) Modeling liquefaction-induced building damage in earthquake loss estimation. *Soil Dynamics and Earthquake Engineering*, 26, pp. 1530. [3] Dashti S., Bray J. D., Pestana J. M., Riemer M., Wilson D., (2010) Mechanisms of seismically induced settlement of buildings with shallow foundations on liquefiable soil. *Journal of Geotechnical and Geoenvironmental Engineering* ASCE, 136, 1, pp. 151-164.

Building Time-Dependent Earthquake Recurrence Models for Probabilistic Loss Computations

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We present a Risk Management perspective on earthquake recurrence on mature faults, and the ways that it can be modeled. The specificities of Risk Management relative to Probabilistic Seismic Hazard Assessment (PSHA), include the need for loss per event to determine the correlation of risk between sites, the non-linearity of the exceedance probability curve for losses relative to the probability for event occurrence, the fact that losses at all return periods are needed (and not at discrete values of the return period), the time-scale of interest, and the set-up of financial models which sometimes require the modeling of realizations of the order in which events may occur (I.e., simulated event dates are important).

We use New Zealand as a case study and review the physical characteristics of several faulting environments, contrasting them against properties of three probability density functions (PDFs) widely used to characterize the inter-event time distributions in time-dependent recurrence models. We review the data available to constrain both the priors and the recurrence process. We propose that with the current level of knowledge, the best way to quantify the recurrence of large events on mature faults is to use a Bayesian combination of models, i.e., the decomposition of the inter-event time distribution into a linear combination of individual PDFs with their weight given by their evidence ratio.

Finally we propose to the community: 1. A general debate on how best to incorporate our knowledge (e.g., from geology, geomorphology) on plausible models and model parameters, but also preserve the information on what we do not know; and 2. The creation and maintenance of a global database of priors, data, and model evidence, classified by tectonic region, special fluid characteristic (pH, compressibility, pressure), fault geometry, and other relevant properties so that we can monitor whether some trends emerge in terms of which model dominates in which conditions.

Advances in Understanding Earthquake Hazard in Central and Eastern North America

Oral Session · Friday · 8:30 AM · 2 May · Room 2 Session
Chairs: Robert Williams, Mitch Withers, William Stephenson and John Ebel

Paleoseismic Evidence for Persistent Intraplate Seismicity Associated with Reactivation of Precambrian Crustal Structures in Central Canada

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Central Canada experiences recurring low to moderate intraplate earthquakes linked to reactivation of poorly- understood Precambrian basement structures. Unfortunately such structures are deeply buried below Paleozoic cover rocks, Pleistocene glacial and postglacial sediments and large lake bodies. Well defined laterally-extensive seismite horizons composed of ball and pillow structures, thrust faults and debrite horizons have been mapped in lengthy outcrops of early to mid-Silurian carbonate and siliclastic shallow marine strata. These structures record sediment disturbance by moderate paleo-earthquakes in the vicinity of the Grenville Front Tectonic Zone and other deeply buried crustal lineaments, and may be associated with phases of rapid subsidence of the Michigan Basin in response to far-field Appalachian orogenic events. Recent earthquake-related deformation in the last 10,000 years is recorded on high resolution seismic sub-bottom profiles that identify sediment faulting, diapiric deformation and slumping on many lake floors located above Precambrian terrane boundaries. Exceptionally thick mass flow successions and extensive faults in Lake Timiskaming located along the floor of the Ottawa-Timiskaming Graben within the seismically active Western Quebec Seismic Zone, suggest a higher frequency of earthquakes and slope failure during deglaciation and rapid glacio-isostatic rebound, but faulting and failure of lakefloor sediments is ongoing confirming the hypothesis that the graben is a weak zone within the North American plate. Results support the model that ongoing mid-plate earthquake activity is a consequence of brittle deformation of the fractured and faulted upper crust of the North American plate with significant implications for the assessment of seismic hazard in vulnerable intraplate regions with ageing infrastructure.

The St. Lawrence Rift System and its Relationships with Recent Earthquakes

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It is generally assumed that most $M > 4.5$ earthquakes of the St. Lawrence Valley occur on faults of the St. Lawrence Rift System (SLRS), a system of faults that include the Ottawa-Bonnechere and Saguenay grabens. Created during the opening of the Iapetus Ocean, faults of the SLRS were created as steeply-dipping normal faults but the current compressive environment reactivates them as reverse faults.

During the 2010–2013 time period, fifteen $mN \geq 4.0$ earthquakes have been located within or near the SLRS. Except for three of those earthquakes, all other earthquakes occurred in the three main seismically active zones, namely Charlevoix (CSZ; 3 events), Western Quebec (WQSZ; 7 events; including two $mN > 5.0$), and Lower St. Lawrence (LSLSZ; 2 events). All earthquakes represented thrust faulting in the mid- to upper crust.

These new earthquakes give us an opportunity to revisit the assumption that they represent the reactivation of SLRS faults. In the CSZ, the recent earthquakes followed the trend defined by the some 35 years of micro-seismic monitoring. Faults related to the SLRS and to a meteor impact structure are possibly reactivated but some earthquakes also occur in what appear to be highly fractured blocks between regional faults.

Earthquakes of the WQSZ tend to concentrate in a well-defined NW-SE alignment. The six local earthquakes of the time period 2010–2013 show the difficulty in relating mid-crustal hypocenters with faults or lineaments mapped at the surface. The May 2013 M 4.5 Ladysmith, Quebec, earthquake occurred near some faults of the Ottawa-Bonnechere Graben but it is difficult to decide which fault was reactivated.

We propose that SLRS faults should not be a priori considered the reactivated structures for most small to moderate earthquakes ($M < 4.5$). It is also possible that local conditions present in a few seismic zones can weaken faults or enhance the stress levels, favoring the occurrence of earthquakes.

USArray Transportable Array Evolving into the Central and Eastern United States Network (CEUSN)

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The Central and Eastern United States Network (CEUSN) is a long-term sub-array of ~160 seismometers selected from EarthScope's USArray Transportable Array (TA) footprint. The mission of the CEUSN is to enable researchers and Federal agencies alike to better address the basic geologic questions, background earthquake rates and distribution, seismic hazard potential, and associated societal risks of this region. The network stems from collaboration between the National Science Foundation, United States Geological Survey, United States Nuclear Regulatory Commission, Department of Energy, and Incorporated Research Institutions for Seismology. Like the Transportable Array, the CEUSN stations are transmitting data in real time, allowing for continuous seismic monitoring. This long-term deployment of seismometers will produce a much larger set of observations than achievable during the originally planned 2-year duration of the TA deployment. The CEUSN, together with the existing coverage of permanently deployed seismometers in the central and eastern United States, will combine to form a network of ~300 broadband stations. The initial stations were deployed in November, and the rest will be operational by May 2012.

Referenced Empirical Ground-Motion Model for Eastern North America, Based on the NGA-West 2 GMPE

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Ground-motion prediction equations (GMPEs), giving expected ground-motion amplitudes as a function of magnitude and distance, are an important component of earthquake hazard analysis. A useful method for development of GMPEs in data-poor regions such as eastern North America (ENA) is the referenced empirical approach (Atkinson, 2008; Atkinson and Boore, 2011), in which sparse observational data are compared to an empirical GMPE from a data-rich region. We compare a recent GMPE for shallow events in active regions (Boore, Stewart, Seyhan and Atkinson, denoted BSSA14), with recorded ground motions in ENA (peak ground motions and response spectra), considering both Central U.S. data (CUS) and data from southeastern Canada and northeastern U.S. (east). We note that BSSA14 is well constrained at low magnitudes (M3.5+), making comparisons to ENA data robust.

Residuals are defined as the ratio of the observed ENA values to the predicted values based on BSSA14. The residuals trends will be a function of frequency and distance, and reflect regional differences in source amplitude and attenuation. We observe that the residuals trends are similar in the CUS and east regions, indicating just slightly higher attenuation in the CUS. The Gulf Coast region, by contrast, shows significantly higher attenuation. In general, at close distances (<60 km), residuals tend to be insignificant except at very high frequencies (>10Hz); this suggests that western-based GMPE models might be used to predict eastern motions in high-hazard regions, for which sources at <60 km dominate (except for frequencies >10 Hz and PGA). As distance increases, the residuals gradually increase, presumably due to the slower attenuation rate at regional distances in ENA compared to that in active regions. The proposed referenced empirical GMPEs can be used for hazard analysis in ENA, in particular to provide empirically-constrained scaling of motions to magnitudes larger than those available in the ENA database.

Comparing the CENA GMPEs using NGA-East Ground Motion Database

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The Next Generation Attenuation (NGA) East project has an updated database for Central and Eastern North America (CENA) ground motions. The objective of this study is to analyze the performance of ground motion prediction equations (GMPEs) used in the United States Geological Survey (USGS) National Seismic Hazard Mapping Project (NSHMP) and some other potential GMPEs used in the CENA. Analyses include bias analysis and checks for model inadequacies using statistical tests such as cumulative probability plots, histograms and boxplots. Ranking of the GMPEs is accomplished using minimum residual, log likelihood (LLH), and Euclidean Distance Based Ranking (EDR) techniques.

From the classical residual analysis, Atkinson and Boore (2011) (model A08p), Atkinson and Boore (2011) (model AB06p) and Atkinson and Boore (2006) (model AB06+) with 200 bar stress drop performed better than other GMPEs. These results were also analyzed using box plots to summarize the location, dispersion, and symmetry or skewness of the residual values. In general the NGA East database is positively skewed i.e., the right tail is more pronounced than the left tail. This implies that most of the observed ground motion values are concentrated to the left of the mean, with extreme values to the right. GMPE logarithmic residuals are leptokurtic and non-normally distributed, although not strongly so. EDR results show models Atkinson (2008) (model A08), AB06p and AB06+ as the best performing models for combined site classes. Models AB06p, EPRI (2004) cluster2 model (EPRI2), AB06+ and Silva et al., (2002) double corner model (SD02) matched the ground motion to the data well in rock sites. Generally, newer GMPEs tend to predict lower ground motion levels than older GMPEs. This is attributed to differences in the geometrical spreading used with the newer GMPEs using $R^{-1.3}$ verses $R^{-1.0}$ in the older GMPEs.

Time Dependence of Magnitude Conversion Relations for Eastern Canada: More Complex than We Thought

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A change of 0.12 in the m_N-M_W relation for eastern Canada in the mid-1990s was previously established and found to be related primarily to changes in instrumentation during a seismograph network upgrade, which led to m_N being calculated at higher frequencies than in the past. The national seismic monitoring network has undergone several previous large-scale upgrades raising the question whether there could have been additional such magnitude relation changes. There are not sufficient instrumental M_W's, the preferred scale for hazard assessment, for past earthquakes for a thorough investigation. There are, however, amplitude-period data in the Canadian earthquake database back to 1940. For recent earthquakes MLg(f) is generally close to M_W. MLg(f) was calculated and compared to m_N for earthquakes in eastern Canada from 1940 through 2012. The difference between the two shows an increase from 0.0 to 0.6 with several steplike increases coinciding with network upgrades. Over the same period a decrease in the average period at which m_N was calculated was noted. Data from recent earthquakes have shown that the difference between MLg(f) and m_N is dependent on both frequency and distance. The same dependence is observed for the older earthquakes. That is, the time dependency of the magnitude relations appears to be related to changes in the input parameters and not directly to the calculations or instruments themselves. One must be careful not to assume that a change in the MLg(f)-m_N relation is conclusive evidence for a change in the m_N-M_W relation. However, these results urge the use of caution in applying a single conversion constant for data amassed over several decades and raise the issue whether there may be similar time dependencies for other magnitude relations and in other regions.

Regional Study of Fourier Amplitude Drop of Lg-Wave Acceleration in Central United States

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The purpose of this study is to use a set of broadband data from the EarthScope Transportable Array (TA) stations to constrain the geometrical spreading and the Q-factor. During 2010–2011 the EarthScope TA recorded abundant data from swarms of small-to-moderate-sized earthquakes in Arkansas, Oklahoma, and Texas. The EarthScope TA has provided important new data to study path attenuation in the central and eastern United States. There are a large number of seismograms with interstation distances of about 70 km and such data are used in this study to estimate the seismic attenuation observed from the drop in the Fourier amplitude of the recorded accelerograms.

The objective of this study is to identify regions of the central United States that exhibit distinctive S-Lg wave propagation. Data from distances up to 1000 km from the earthquake source are considered in order to quantify regional differences for geometric spreading and the Q factor, specifically as associated with the Lg phase in the mid-continent and Gulf Coastal regions.

High-Resolution Aeromagnetic Data Illuminate Crustal Structure Associated with the New Madrid Seismic Zone, Missouri and Arkansas

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In 2013, the U.S. Geological Survey completed a high-resolution aeromagnetic survey in the New Madrid seismic zone (NMSZ). Our goal was to map and characterize crustal structure and contribute to ongoing earthquake-hazard investigations. The survey was flown along NW-directed flight lines spaced 400 m apart at a height of 200 m above ground. The survey spans Crowley's Ridge, the NW margin of the Reelfoot rift, and the southern arm of the NMSZ, and was designed to overlap a high-resolution LiDAR survey completed in 2012 to allow for cross-comparison of features found on both datasets. Power lines, pipelines, and town infrastructure dominate parts of the survey but their anomalies were attenuated with matched-filter analysis. The remaining crustal magnetic field is remarkably smooth, reflecting very low magnetizations of near-surface rocks and deposits. Nevertheless, aggressive data processing allowed us to illuminate detailed near-surface (upper 2 km) crustal features apparently at the top of Precambrian basement northwest of and mostly striking parallel to the Reelfoot rift NW margin. The most prominent of these anomalies corresponds with the Commerce geophysical lineament. Other shallow anomalies indicate basement structure and/or contacts. One of these strikes NE, crosses the entire survey (41 km), and corresponds with an alignment of three LiDAR topographic scarps interpreted as tectonic in origin but not associated with earthquakes in the modern record. The magnetic survey found no evidence of near-surface faults directly responsible for ongoing seismicity in the southern arm of the NMSZ. Various explanations are possible: (1) Near-surface lithologies in this part of the Reelfoot rift may be virtually nonmagnetic. (2) Faults in the southern arm of the NMSZ do not juxtapose lithologies with contrasting magnetic properties. (3) The southern arm of the NMSZ is short-lived, with insufficient time to accumulate discernible slip on individual faults.

Relative Locations of Earthquakes and Potential Driving Mechanisms of Seismicity Along the Northeast U.S. Atlantic Passive Margin

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Understanding the possibility of a large magnitude, tsunamigenic earthquake along the continental shelf break of a passive margin is important as events similar to the 1929 M7.2 Grand Banks earthquake can unexpectedly devastate coastline towns. The tsunamigenic Grand Banks event raises the question, what is the potential for such an event to occur along other parts of the northeast Atlantic margin? Moderate seismicity has been observed near the continental shelf break east of the Gulf of Maine (~1000km southwest of the Grand Banks event). From 2008–2013 there were 16 earthquakes ranging in magnitude from 2.0–3.9 along the Gulf of Maine continental shelf break, with 10 of the earthquakes occurring on 12 April 2012. This research focuses on identifying the spatial and temporal migration patterns of these earthquakes calculated using a double-difference relative location analysis. In this procedure two waveforms are cross-correlated to determine the difference of arrival times of the P-waves and of the S-waves. The program then calculates the location of one event relative to another based on these differences in arrival times. The data show that generally as the earthquakes occurred further northwest they also happened deeper in the crust. Plotting the relative longitude versus relative latitude versus relative depth shows that the earthquakes map out a planar surface. If the events occurred on a single fault, then the preliminary interpretation of that fault is the strike is in the range from N60°E to N66°E, the dip is in the range from 23°–27.5° and the faults total extent is ~2.4km by ~2.7km. If this entire area ruptured in one earthquake, the event would be about a magnitude 5.0. The seismic hazard in the Gulf of Maine region will be better constrained with continued research on focal mechanisms of the 2012 events and by comparing the results of the locations and magnitudes of the 2012 events to those of the 1929 tsunamigenic Grand Banks event.

Recent Earthquakes in the Central and Eastern U.S. Prompt Variable Responses to Reduce Future Earthquake Losses

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The increase in earthquakes in the Central and Eastern U.S. over the last four years, including the events in central Virginia (M5.8) and central Oklahoma (M5.6), caused alarm and significant losses in some cases (Virginia earthquake: about $200 million; Oklahoma earthquake: about $3–5 million), but no loss of life. This part of the U.S. is not accustomed to strong and damaging earthquakes. There has been a variety of State, Federal, and private entity responses to these earthquakes in terms of rebuilding structures, building code changes, and calls for citizens to add earthquakes to their list of natural disaster preparedness. Long-lived swarms of small magnitude felt earthquakes in Texas and Oklahoma, many occurring in areas that have been historically aseismic, have also caused concern among local citizens, prompted community meetings, and led to an unprecedented call in 2013 by the Oklahoma State Insurance Commissioner for citizens to purchase earthquake insurance.

The M5.8 2011 Central Virginia earthquake, located about 120 km southwest of Washington D.C., damaged several iconic structures in D.C. including, for example, the 170-m tall unreinforced masonry (URM) Washington Monument, the 100-m high URM National Cathedral, and Smithsonian Castle. Damage to these structures included cracking and spalling of structural stone and toppling of decorative stone masonry elements. Repairs to the National Cathedral (about $26 million) will include significant seismic strengthening upgrades while the Washington Monument (repairs about $15 million) will receive minor seismic upgrades. Shaking from the 2011 M5.6 Oklahoma earthquake caused about $1 million damage to a 100-year-old brick building on the St. Gregory's University campus in Shawnee, Oklahoma. Repairs to this structure involved significant seismic upgrades to the iconic turret features that are intended to improve the life-safety performance of this building in future earthquakes.

New Directions in PSHA: Ins, Outs, and Uncertainty

Oral Session · Friday · 1:30 PM · 2 May · Room 2 Session
Chairs: Peter Powers, Morgan Moschetti and Ned Field

Incorporating Time Dependence in PSHA in the (Near) Absence of Data

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Recent work to update the seismic source characterization (SSC) for PG&E's Diablo Canyon Power Plant (DCPP) has highlighted the potential for traditional PSHA practice to understate uncertainty in seismic hazard where a Poisson (random in time) recurrence model is assumed. The Poisson model is commonly used where little is known about fault recurrence rates or time since the most recent events (MREs) because of its simplicity and its association through information theory with being least prescriptive. On the other hand, paleoseismic studies in California and New Zealand show recurrence coefficients of variation (CV) smaller than would be predicted by a random-in-time model and more consistent with a renewal model and some form of time dependence. If faults near DCPP behave similarly, their hazard could be lower or higher than the long-term average depending on time since the MREs. An initial sensitivity analysis shows that recurrence model uncertainty on fault sources is a major contributor to SSC uncertainty for DCPP. The challenge for the DCPP SSC update is to incorporate uncertainty in earthquake recurrence models for its nearby fault sources given very little concrete information on past large earthquakes aside from their absence in the historical record. Our approach is to incorporate earthquake recurrence as epistemic (model) uncertainty on fault sources with alternative branches for a Poisson process and time dependent hazard expressed as multiples of the equivalent Poisson rate. The alternative branches are formed by considering functional forms of earthquake recurrence, CV values informed from empirical data, limited fault-specific data on timing of past earthquakes, and whether the faults are early or late in their cycle.

Computing Elastic-Rebound-Motivated Earthquake Probabilities in Un-segmented Fault Models – The UCERF3 Methodology Supported by Physics-based Simulators

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A methodology is presented for computing elastic-rebound-based probabilities in an un-segmented fault or fault system, which involves computing along-fault averages of renewal-model parameters. The approach is less biased and more self-consistent than a logical extension of that applied most recently to multi-segment ruptures in California. It also enables the application of magnitude-dependent aperiodicity values, which the previous approach does not. Monte Carlo simulations are used to analyze long-term system behavior, which is found to be generally consistent with that of physics-based earthquake simulators. Results cast doubt that recurrence-interval distributions at points on faults look anything like traditionally applied renewal models, a fact that should be considered when interpreting paleoseismic data. We avoid such assumptions by changing the 'probability of what' question (from slip at a point to the occurrence of a rupture, assuming it is the next event to occur). The new methodology is simple, although not perfect in terms of recovering long-term rates in Monte Carlo simulations. It represents a reasonable, improved way to represent first-order elastic-rebound predictability, assuming it is there in the first place, and for a system that clearly exhibits other complexities like aftershock triggering.

How We Can Combine Epidemic Type Aftershock Sequences (ETAS) and Finite Source Rupture Models?

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Epidemic Type Aftershock Sequences (ETAS) represent a point process model in which future triggered events (children) are expected to occur at a given time and location, controlled only from previously observed events (parents events). These statistical forecast models are earthquake-catalog based, without including any information related with the physical mechanism of earthquake nucleation and triggering. However, assuming that a significant earthquake such as the Loma Prieta M=6.9 or the Landers M=7.3 is a point-process has obvious biases since it involves fault rupture along a 40 and 80 km fault, respectively. Finite fault source models are now routinely developed for major earthquakes with magnitude greater than 6.5 based on geodetic, seismic and strong motion data and they are usually available within few days after the mainshock. In this study I combine the Uniform California Earthquake Rupture Forecast (UCERF) generic ETAS model for California, based on the modern instrumental catalog with M greater than M=2.5, with the available finite source models of the 1989 Loma Prieta and 1992 Landers events. I compare the forecasted seismicity rates between the ETAS, the hybrid Finite Source ETAS (f-ETAS) models and the observed seismicity for the first 100 days following each mainshock. I assess possible sources of uncertainty for the f-ETAS model and test for the spatial consistency of the forecast models using log-likelihood statistics. The results support that the f-ETAS models present an improved spatial consistency along the rupture plane. Finally, I focus on a comparison between three statistical ETAS models (generic, sequence specific and the f-ETAS model) and their physics-based (Coulomb Rate/State) counterpart developed using the best available source

model for Loma Prieta earthquake. For operational forecast purposes the f-ETAS model could improve our short-term predictability depending on the availability and the quality of the source model.

Probabilistic Seismic Hazard Analysis Using the Single Station Sigma Concept: Application to a New Nuclear Site

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A key component of probabilistic seismic hazard analysis (PSHA) is the quantification of aleatoric variability (e.g., the standard deviation of ground motion prediction equation). The large availability of ground motion data in recent years has allowed for significant improvements in the way that uncertainty is quantified. In particular, dense ground motion networks allow for the separation of the contributions of source and site effects to total standard deviation. Single station sigma is the standard deviation that results when the site-to-site variability is removed from the total aleatoric variability. This reduction in aleatoric variability is justified only if the site term (i.e., the repeatable site effects) and its epistemic uncertainty are estimated at the site under analysis and incorporated into the PSHA. Hence, the concept of single-station sigma implies shifting the site term variability from aleatoric variability to epistemic uncertainty. The use of single-station sigma in PSHA has constituted one of the most significant advances in hazard analyses in the last decade. The single-station sigma concept was applied for a new-build nuclear power site in South Africa. The absence of recordings at the site implied the need to estimate the site term using analytical methods. This estimate included two equally important parts: accounting for the deep crustal response and damping (through Vs-kappa adjustments of the ground motion prediction equations used in the hazard analyses), and the response of the near-surface geological deposits. Recordings of small magnitude earthquakes at analog sites were used to quantify the damping (i.e., kappa) at the site, and an extensive site investigation was undertaken to obtain the shear wave velocity of the near-surface deposits. The analyses included a proper accounting of all sources of uncertainty to properly quantify the epistemic uncertainty on the site term.

Using the Averaging-Based Factorization to Assess Low Frequency ($<$ 0.5 Hz) CyberShake Hazard Models

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The SCEC CyberShake project combines stochastic models of finite-fault ruptures with 3D ground motion simulations to compute seismic hazards in Southern California. The first CyberShake hazard model (Graves et al., 2011) used the Graves & Pitarka (2004) rupture model (GP-04) and the Kohler et al. (2004) community velocity model (CVM-S). We have recently extended the CyberShake calculations to include the Graves & Pitarka (2010) rupture model (GP-10), which increases the rupture complexity relative to GP-04, and the Shaw et al. (2011) community velocity model (CVM-H), which features different basin structures than CVM-S. Here we apply the averaging-based factorization (ABF) technique to compare CyberShake models and assess their consistency with the Next Generation Attenuation (NGA) models. ABF uses a hierarchical averaging scheme to separate the shaking intensities for large ensembles of earthquakes into relative (dimensionless) excitation fields representing site, path, directivity, and source-complexity effects, and it provides quantitative, map-based comparisons between models. The CyberShake directivity effects are generally larger than predicted by the Spudich & Chiou (2008) NGA directivity factor, but those calculated from the GP-10 sources are a factor of two smaller than those of GP-04, owing to the greater incoherence of the wavefields from the more complex rupture models. The CyberShake basin effects are generally larger than those from the three NGA models that provide basin-effect factors. However, the basin excitation calculated from CVM-H is smaller than from CVM-S, and shows stronger frequency dependence, primarily because the horizontal dimensions of the basins are much larger in CVM-H. The NGA model of Abrahamson & Silva (2008) is the most consistent with the CyberShake CVM-H calculations, with a basin-effect correlation factor greater than 0.9 across the frequency band 0.1–0.3 Hz.

Visualizing the Range of Epistemic Uncertainty of GMPEs

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The accurate description of epistemic uncertainty is a key aspect in probabilistic seismic hazard analysis. This applies in particular to the ground-motion part, as the use of different ground-motion prediction equations (GMPEs) can lead to very different results for low exceedance frequencies. To account for epistemic uncertainty, different models are combined in a logic-tree framework. In order to capture the full range of epistemic uncertainty, it is important to include models that are sufficiently different from each other – on the other hand, they should not overestimate the uncertainty. However, it is difficult for a human expert to fully appreciate the differences between models – they may vary in various aspects, such as their magnitude and/or distance scaling. Building upon the work of Scherbaum et al. (2010), we show how it is possible to examine all models as a whole by visualizing them in a low (two or three) dimensional space. Therefore, we evaluate different GMPEs at different values values of their predictor variables such as magnitude and distance, which creates a point in a high-dimensional space for each model. The models are then projected down to two or three dimensions, retaining their relative alignment in the high-dimensionsal space. By including reference models with known differences between them, directions in the low-dimensional space can be identified in which the magnitude and distance scaling of the models change. To facilitate a physical understanding, the GMPEs are projected together with simulations of the point source stochastic model at different parameter values of e.g. stress drop, kappa and others. Changes of the physical parameters occur along specific directions in the low-dimensional space, which allows to assess relative physical differences between the GMPEs. Together with the distribution of the GMPEs in the low-dimensional space, this information allows to assess the range of their epistemic uncertainty.

Comparison of Epistemic Uncertainty in Hazard in California between UCERF2 and UCERF3

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The National Seismic Hazard Mapping project develops time-independent mean hazard curves for use in building codes and other applications. The development of the hazard map includes both aleatory and epistemic uncertainty. Epistemic uncertainty is captured by a range of model parameters (e.g., the range of maximum magnitudes for gridded seismicity sources), multiple expert interpretations (e.g., different moment-area relationships), and statistical uncertainty (e.g., recurrence rate). These uncertainties are represented via logic trees and associated branch weights. Hazard calculations are performed for each logic-tree branch and the mean hazard curve is computed from the weighted combination of all branches. The variation in the results from each of the branches defines the epistemic uncertainty in seismic hazard. With the release of the third version of the Uniform California Earthquake Rupture Forecast (UCERF3) the number of logic tree branches has increased from 480 in UCERF2 (2007) to 1440 in UCERF3 (2013), thereby broadening the epistemic uncertainty in the seismic hazard. In this study, we compare the uncertainty in the seismic hazard based on UCERF2 and UCERF3 for a few sites in California. The results from UCERF2 consider the three ground motion prediction equations (GMPEs) from NGA-West1 (2008), whereas those for UCERF3 models consider the five GMPEs from NGA-West2 (2013). This contributes to greater uncertainty in the hazard results based on UCERF3. Although we consider epistemic uncertainty in long-term earthquake rates, we do not consider that associated with short-term recurrence rates and a time-dependent model.

Testing for Ontological Errors in Probabilistic Seismic Hazard Models

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Models used in probabilistic seismic hazard analysis (PSHA) comprise two types of uncertainty, aleatory variability describing the intrinsic randomness of the earthquake-generating system, and epistemic uncertainty characterizing our lack of knowledge about the system. Prospective testing evaluates how well a PSHA model forecasts new observations. Model rejection exposes 'unknown unknowns'; i.e., ontological errors in the representation of the system and its uncertainties. We clarify the conceptual issues associated with the testing of PSHA models for ontological errors in the presence of aleatory variability and epistemic uncertainty. Among

the concerns is the use of expert opinion to characterize epistemic uncertainties; many have argued that such personal degrees of belief cannot be measured and, by implication, cannot be tested. We show that testability of the ontological (null) hypothesis derives from an experimental concept, external to the model, that identifies sets of data judged to be exchangeable under the experimental conditions. Exchangeable data are realizations of random variables whose joint probability distribution, when conditioned on the explanatory variables, is invariant with respect to permutations in data ordering. Exchangeable data can therefore be modeled as i.i.d. random variables with a well-defined frequency of occurrence. Exchangeability judgments play a key role in our theory because they formalize the concepts of aleatory variability and epistemic uncertainty, and they set up an error-statistical regime for ontological testing based on prior predictive p-values, which involves an interesting interplay between Bayesian and frequentist methods. We illustrate PSHA testing regimes with some simple examples of experimental concepts, and we show how proper accounting for epistemic uncertainties avoids incorrect inferences and inapt comparisons found in the recent literature.

Effects of Various Declustering and Smoothing Methods on Earthquake Catalogs and Consequences for Seismic Hazard and Seismic Risk in New Zealand

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We apply different declustering methods, temporal completeness estimates, and smoothing techniques to the New Zealand earthquake catalog to estimate regional seismicity rate changes and the consequent impact on earthquake hazard and risk in the area. We explore the sensitivity of the declustering parameters (e.g. Reasenberg, 1985) as well as the variable magnitude and time windows (e.g. Gardner and Knopoff, 1974) on the magnitude-frequency relationships derived from declustered catalogs for the background zones in New Zealand. In addition, we test the effect of temporal completeness interval estimates and smoothing methods. We incorporate background rate estimates from the full catalog and compare them with the range of background rates from all of the declustering, completeness, and smoothing methods to our hazard model. We then compare a suite of metrics between the full catalog rates and the models with different rates to assess 1) the impact on hazard and risk and 2) the epistemic uncertainty associated with the range of catalog declustering and smoothing techniques. In areas where the seismic hazard is dominated by larger crustal faults (e.g. Wellington) the choice of declustering and smoothing methods has little to no impact on the hazard or risk. However, in areas like Auckland where the background zone contribution to the seismic hazard is greater, the choice of techniques is more significant (Christophersen et al., 2011). However, the impact of the seismic risk is less significant due to the lower estimated ground motions.

The Global Earthquake Activity Model: What it is, What it can do, and How it Can Be Tested

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Scientists from UCLA, UNR, USGS, the Global Earthquake Model project (GEM), and the Collaboratory for Study of Earthquake Predictability (CSEP) are collaborating to construct and test a fully global estimate of earthquake rates as a function of magnitude at 0.1 by 0.1 degree resolution. The model, nicknamed GEAR, is based on instrumental earthquake catalogs and a global strain rate model (GSRM). GEAR covers the magnitude range 5.8 and above and includes focal mechanism estimates with their uncertainty.The strain-rate component provides temporal stability and spatially continuous deformation rates, while the seismicity component allows the forecast to evolve slowly. The normalized magnitude distribution in each cell will be a tapered Gutenberg-Richter distribution, or weighted sum of those, with b-values and corner magnitudes determined by a very limited number of global parameters. The seismic and strain-rate components of the model are specified separately and then combined optimally to fit earthquake occurrence over the last several years. Because it forecasts epicenters rather than ruptures, it can easily be tested using likelihood scores and other methods currently employed by CSEP. Because of its simplicity, GEAR can serve as a well-vetted reference model for studies with more complex behavior, and it can also serve as a null-hypothesis against which more complex models can be tested. Because of its high spatial resolution, GEAR can be compared with detailed regional models as well. By comparing GEAR with alternate models, we can address some enduring scientific questions: Do really large earthquakes come from a difference population from smaller ones? Do large earthquakes cluster, or do they consume enough strain energy to prevent future ones? Are the factors that control earthquake statistics relatively uniform, and highly variable from region to region?

Seismic Location and Processing Techniques

Oral Session · Friday · 8:30 AM · 2 May · Room 3 Session Chairs:

Hypocentral Relocations Aided by Virtual Receivers Constructed via Seismic Interferometry

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A 3D elastic wave propagation program[1] was used to investigate whether the technique of[2] can improve hypocentric relocations by employing virtual receivers (VRs) near a cloud of microearthquakes.

The VR technique can be loosely described as a "dual" of the ambient noise technique from seismic interferometry – replacing noise sources on the boundary of a region of interest with physical receivers. Seismograms from events in the interior of the region of interest can be cross-correlated and integrated over all boundary receivers to estimate a seismogram from one of the interior events as if it were recorded at the location of another interior event.

Unlike ambient noise interferometry, where raypaths from all directions impinge on the region of interest, VR raypath directions are constrained by the location of the physical receiver array. Hence, approximating the surface integral plays a large role in the practical success of the technique. Fortunately, stationary-phase arguments suggest that only a few physical receivers nearby the interior-source to virtual-receiver ray direction suffice to reconstruct the seismogram[2].

Arrival time error statistics and relocations of perturbed synthetic hypocenters using virtual receiver arrivals will be shown at the meeting. Improved performance in hypocc[3] – by replacing the embedded LSQR solver with LSMR[4] – will also be discussed.

References:

[1] Petersson, N. A., & Sjogreen, B. (2011). User's guide to WPP version 2.1.5. LL Nat'l Lab.

[2] Curtis, A., Nicolson, H., Halliday, D., Trampert, J., & Baptie, B. (2009). Virtual seismometers in the subsurface of the Earth from seismic interferometry. Nature Geosci., 2 (10), 700–704.

[3] Foulger, G. R., & Julian, B. R. (2013). Seismological software for geothermal monitoring. SGP-TR-198. Stanford University.

[4] Fong, D. C., & Saunders, M. (2011). LSMR: An iterative algorithm for sparse Least-Squares problems. SIAM Journal on Scientific Computing, 33 (5), 2950–2971.

Real-time Automatic Detectors of P and S Waves Using Singular Value Decomposition

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We implement a new method for automatic detection of P and S phases using Singular Value Decomposition (SVD) analysis. The method is based on a real-time iteration algorithm of Rosenberger (2010) for the SVD of three component seismograms. The algorithm identifies the incidence angle by applying SVD and separates the waveforms into their P and S components. We apply the algorithm on filtered waveforms and then either set detectors on the incidence angle and singular values, or apply Signal-to-Noise Ratio (SNR) detectors for P and S picking on the filtered and SVD-separated channels. A recent deployment in the San Jacinto Fault Zone area provides a very dense seismic network for testing the detection algorithm in diverse setting, including events with different source mechanisms, stations with different site characteristics, and ray paths that diverge from the approximation used in the SVD algorithm. A Butterworth band-pass filter of 2–30 Hz gives the best performance in a large variety of events and stations. We tested the SVD detectors on many events and present results from one of the most complex and intense aftershock sequence of the MW 5.2 – June 2005 event. This sequence was thoroughly reviewed by several analysts, identifying 294 events in the first hour, located in a dense cluster around the main shock. We used this dataset to fine-tune the automatic SVD detection, association and location, reaching a 37% automatic identification and location of events. All detected events fall within the dense cluster and there are no false events. An ordinary SNR detector does not exceed the 11% success and has a wider spread of locations (not within the reviewed cluster). One of the main advantages of the SVD detectors is the pre-knowledge of the phases

picked (P or S), reducing significantly the noise created by ordinary 'blind' SNR detectors.

The Effects of Measurement Uncertainties on the Estimation of Seismic Gradients

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Estimating the spatial gradients of a seismic wavefield has applications in seismic strain estimations, rotational motion estimates, and seismic gradiometry. Typically, seismic gradients are estimated using a small-scale seismic array of well-calibrated instruments to record the wavefield. The array stations occupy discrete coordinates in some sort of finite element grid and the spatial derivatives are estimated numerically. It's well known that the nominal aperture of the array must be smaller than 0.1 wavelengths to avoid numerical artifacts with estimating the spatial derivatives of the wavefield. However, there is little known regarding the minimum aperture of an array for reliable gradient estimation. Specifically, we can show that for given uncertainties in station coordinates and/or amplitude response, the uncertainties in the gradients are inversely proportional to array aperture. Our primary goal for the work shown here was to quantify this phenomenon. Our secondary goal was to devise a way to construct confidence intervals for the estimated spatial gradients. We perform a series of Monte Carlo simulations on synthetic array data to find an optimal array aperture that minimizes the uncertainty in the computed gradients (and attributes derived from them) for a given amount of measurement uncertainties. We then analyze actual seismic data from a high-frequency seismic array as well as a broadband seismic array. Both of these arrays were constructed specifically to estimate seismic gradients. By choosing specific stations within each array, we are able to vary the nominal aperture of the arrays between 0.01 and 0.1 wavelengths. We then compare our simulations with our actual data, and compute confidence intervals.

Doing More with Short Period Data: Using Coda Envelopes to Estimate Magnitudes for Clipped and Over-Run Earthquakes

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One critical piece of information that seismologists try to ascertain during volcanic unrest is the total seismic energy release and its rate of increase. Seismic energy release is determined by summing earthquake magnitudes and is related to processes such as the volume and rate of intrusion or dome growth. Calculating earthquake magnitudes is a relatively straightforward process when seismograms are 'clean,' i. e. the signal is neither clipped nor over-run by ensuing events. It becomes more difficult to calculate magnitudes, however, when intense swarms produce events that saturate the signal and/or overlap the coda of previous events. Through an iterative process of downsampling and smoothing seismograms, I developed a methodology to draw 'envelopes' that reliably characterize the unique shape of high frequency, low frequency, and hybrid events. The methodology is developed with data from the 2004–2008 eruption of Mount St. Helens. The combination of a well-documented seismic network and a well-documented eruption makes these data ideal for calibrating automated event analysis algorithms. The local and duration magnitudes calculated from these envelopes, which are drawn to preserve maximum amplitude and coda duration, are calibrated against PNSN analysts' picks to ensure reliability and accuracy. Moreover, the envelope's generalized shape allows it to be matched to partial envelopes for signals that are clipped and/or over-run. In doing so, the procedure of analyzing envelopes to determine event magnitude allows for more reliable quantification of seismic energy release during seismic episodes that are too intense for the installed network. The methodology is designed to be easily transportable from instrument to instrument and network to network. It has direct applicability towards volcanoes with limited networks where quick deployment of additional instrumentation is not a feasible way to get more information during intensifying periods of activity.

Identification and Extraction of Surface Waves from 3-Component Seismograms based on the 'Normalized Inner Product'

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Identification of different wave types in a seismogram is an important step for the understanding of wave propagation phenomena. Since in most seismograms, different types of waves with different frequencies may appear simultaneously, separation of waves is more effectively achieved when a time-frequency analysis is performed. In this work, we propose a new time-frequency analysis procedure to identify and extract Rayleigh and Love waves from three-component seismograms. We adopt the Stockwell Transform for the mapping between time and time-frequency domains, because 1) we retain the absolute phase of each localized frequency component, 2) its invertibility allows for the wave extraction by simple filtering in the time-frequency domain. Exploiting the advantage of the absolute phase preservation by the Stockwell Transform, we then construct time-frequency filters to extract waves based on the 'Normalized Inner Product' (NIP). Since the NIP is the time-frequency counterpart of the correlation, Rayleigh and Love waves can be identified depending on the NIP between the Stockwell Transforms of the horizontal and vertical displacement components. The novelty and advantage of the proposed procedure is that it does not require making any assumptions regarding the direction of propagation of the surface waves, but in fact such direction is a byproduct. Furthermore, it is shown that the NIP is a more stable parameter in the time-frequency domain when compared to the instantaneous reciprocal ellipticity, and thus it avoids smoothing (and with it, altering) the data. The procedure has been successfully tested with real signals, in particular to extract Rayleigh and Love waves from seismograms of one aftershock of the 1999 Chi-Chi earthquake recorded on the West Coastal Plain in Taiwan. With the proposed procedure we found different directions of propagation for retrograde and prograde Rayleigh waves, which might suggest they are generated by different mechanisms.

Recent Advances and Findings in Earthquake Geology and Paleoseismology

Oral Session · Friday · 10:45 AM · 2 May · Room 3 Session
Chairs: Scott Bennett and Christopher DuRoss

Third Generation Paleoseismology: Clustering, Segmentation, Supercycles and Paleo Slip Models

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Third generation paleoseismology is moving beyond event identification and dating, and to some extent beyond simply establishing long recurrence statistics. Long and detailed paleoseismic records afford uncommon opportunities to examine recurrence models, clustering, segmentation, interaction with other faults, long term strain history and paleo slip characteristics. A 10,000 year onshore-offshore record in Cascadia and a 16,000 year marine record at the Hikurangi margin have identified periods of clustering and quiescence in the record. In Cascadia, clusters of 4–5 events, with gaps of 700–1200 years between clusters are unlikely to be randomly generated. In Cascadia, a pattern of decreasing recurrence time in at least four segments southward, from ~500–530 years in the north, to ~240 years or less in the south, consistent with geologic structural barriers. Long turbidite records for Cascadia and the Northern San Andreas Fault suggest that these two faults have virtually the same average recurrence interval through the Holocene, and may have a stress transfer relationship across the triple junction. Paleoseismology is beginning to reveal information about magnitudes and has potential to reveal slip patterns of paleoearthquakes. Finally, energy in plate boundary fault zones may have long term cycling involving many seismic cycles. Several lines of evidence, both direct and indirect suggest that the connection between interevent time and earthquake magnitude, and models predicated on this relationship, may be relatively weak. In Sumatra, precisely dated coral evidence has illuminated long term energy cycling of the central Sumatran margin. In Cascadia, similar cycling is apparent based on balancing consistent records of turbidite mass (energy release) against plate convergence (energy gain). Long-term cycling may explain mismatches between deformation models based on interevent times in the last 4600 years and coastal paleoseismic data.

A 3D Marine Paleoseismology Investigation Offshore South Central Coastal California

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As part of the Central Coastal California Seismic Imaging Project, high-resolution marine seismic-reflection data were acquired offshore south central coastal California in 2011 and 2012. These data were collected using a high-resolution 3D Low Energy Seismic Survey (LESS) system consisting of a PCable with 14 hydrophone streamers and a 3-plate boomer acoustic source. The LESS data were collected in three survey areas, San Luis Obispo Bay, Estero Bay and offshore Point Sal, to image faults, buried channels, and other features that can be used as piercing points for estimating slip-rates along the Shoreline, Oceano and Hosgri fault zones. Detailed mapping in San Luis Obispo Bay reveals that the trace of the Shoreline fault is crossed by a complex of Pleistocene low-stand paleochannels

carved into bedrock and buried by marine and non-marine sediment. Possible ages of these channels are estimated from Quaternary sea level curves. A paleoshoreline developed in Quaternary strata also crosses the Shoreline fault, providing an additional piercing point for that fault. Analysis of 3D seismic and other 2D low and high-energy seismic-reflection data from the Estero Bay and Point Sal study areas reveals channels preserved in the stratigraphy of the outer continental shelf and upper continental slope on both sides of the Hosgri fault zone. Ages of these channels are estimated from their relationships to Pleistocene sequence stratigraphic boundaries and deeper unconformities previously mapped in the offshore Santa Maria basin. These channels are used as piercing points to evaluate the slip-rate of the Hosgri fault in both study areas.

10 m Slips on the Pitas Point Thrust: M8 Earthquakes in the Western Transverse Ranges of Southern California

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Slip on the Pitas Point thrust produces uplift and folding of the Ventura Avenue anticline (VAA) in the western Transverse Ranges (WTR) of southern California. Rapid convergence has resulted in as much as 2.7 km of uplift on the VAA over the past 200–300 ka, with as much as 320 m in the past 45–50 ka, indicating a long-term uplift rate of 6–7 mm/yr. Using vintage aerial photography form the 1920's through 1950's prior to construction of the 101 freeway, along with differential GPS and LiDAR, we mapped remnants of four emergent Holocene marine terraces between Carpinteria and Ventura, the youngest three of which are reasonably well-preserved and dated between Punta Gorda and Pitas Point. The most recent emergence event uplifted a Chumash Indian village at Pitas Point by 5–6 m about 900 years ago; this 1st terrace is nearly continuously preserved to the fold crest reaching an altitude of 7–8 m, which implies 9–10 m of slip on the causative fault at depth. Nearly 50 radiocarbon dates on marine shells and culturally derived charcoal indicate terrace emergence at about 0.9 ka, 1.9 ka, and 4.2–4.7 ka, with the 4th (highest and oldest) terrace inferred to be slightly older than 6.5 ka. The Holocene uplift rate indicated by the emergent terraces is 5–6 mm/yr, similar to the long-term rate. Scaling relationships between fault slip, earthquake magnitude, and rupture length suggest that paleo-earthquakes were close to M8, similar to the 1999 Chi Chi or 2008 Wenchan earthquakes, and that ruptures likely included both onshore and offshore faults. Large uplifts in the offshore may have also resulted in local tsunamis along the Santa Barbara and Ventura coasts. High-resolution CHIRP seismic reflection data acquired across the VAA offshore Rincon Point in summer 2013 show evidence for discrete folding/uplift events that are captured in the Holocene sediment record and complement the onshore studies.

Multi-Method Measurement of Offset from the 1857 Fort Tejon Earthquake along the San Andreas Fault in the Carrizo Plain at Channel Sieh31

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Recent work using computer-based analytic tools and LiDAR topography suggested that offset during the 1857 Fort Tejon earthquake along the Carrizo section of the San Andreas fault was 5–6 m, significantly lower than the previously reported 8–10 m using traditional on-the-ground measurements. We are reevaluating surface displacement of the great 1857 Fort Tejon earthquake using 3D excavation of channel Sieh31, which has been interpreted to have been offset ~6m and ~9m by researchers using different methods. Increasing availability of high resolution topography and imagery make remote measurements more common. Continued validation of remote and field-based measurements is essential. We selected channel Sieh31 as the best candidate to measure 1857 slip and investigate the potential for superposed tectonically offset older and deflected younger sections of a single channel. In preliminary 2013 work, 3 trenches exposed well-defined channels incised into stratified alluvial fan deposits. The excavations show that the original thalweg of the Sieh31 does not coincide with either the present day thalweg nor the median of the present-day channel margins, emphasizing the importance of measuring the offset with a future 3D excavation. Preliminary optically stimulated luminescence (OSL) dates from an earlier channel fill stratum indicate that incision of Sieh31 channel predates ~1750+−30 A.D. While additional data are needed for confirmation, if the channel records a single offset, its age implies that the penultimate earthquake occurred between ~1650 and ~1750 A.D. Thus, the incision of channel Sieh31 predates the great Fort Tejon earthquake and the channel age is ideal to constrain displacement caused by the 1857 earthquake at this location. Preliminary results suggest different geomorphic and geologic measurements of tectonic displacement, and emphasize the importance of validation of surface offset reconstructions from remotely interpreted digital topographic data.

3D Comparison of Coseismic Fold Deformation for the Last 5 Events Across a Releasing Step-over at the Frazier Mountain Paleoseismic Site, Southern San Andreas Fault, CA

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Transtensive step-overs, known as sags, are among the most ubiquitous features of strike slip faults. These structures create closed depressions that collect sediment, are often wet, and thus preserve organic material that can be used to date the thick and rapidly accumulating section. It is clear from historical ruptures that these depressions grow during earthquakes. At the Frazier Mountain paleoseismic site, the main trace of the southern San Andreas creates two adjoining right step-overs, ~30 m x 70 m and ~10 m x 40 m in size. 34 paleoseismic trenches spanning both step-overs show stratigraphic and structural relationships that demonstrate progressive coseismic fold and fault deformation. Earthquakes rupturing through the site have repeatedly down-dropped both step-overs through folding and faulting, producing dramatically thickened growth strata immediately above the earthquake ground surfaces. We quantify structural relief in individual ruptures across the step-overs using surveyed three dimensional point data for stratigraphic surfaces. Offset channels near the site suggest the 1857 earthquake (event E1) generated ~5 m of lateral slip, and we document ~1 m of structural relief across the sag during 1857. Preliminary 3D analysis suggests two prehistoric events, E2 and E5, are similar in size to 1857, especially in fold amplitude where the data overlap. Event E3 has slightly less fold amplitude, but over a larger area, and is unique with widespread surface cracking but few distinct fault offsets, so is difficult to compare. Event E4 is almost certainly smaller, generating about 1/2 the structural relief observed at the 1857 event horizon, suggesting significantly less lateral slip at Frazier Mountain in this event.

A Tale of Two Seisms Down Under: 23 March 2012 Mw 5.4 Ernabella and 9 June 2013 Mw 5.6 Mulga Park

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On 23 March 2012 a MW 5.4 intraplate earthquake occurred in the eastern Musgrave Ranges of north-central South Australia, near the community of Ernabella (Pukatja). This was the largest earthquake recorded on mainland Australia in the past 15 years and resulted in the formation of a 1.6 km-long surface deformation zone that included reverse fault scarps with a maximum vertical displacement of ~0.5 m (average ~0.1 m), extensive ground cracking, and numerous rock falls. Fifteen months later, on 09 June 2013 a MW 5.6 earthquake (the Mulga Park earthquake) occurred ~15–20 km northwest of the 2012 rupture. The P-axes of the focal mechanisms constructed for both events indicate northeast-oriented horizontal compressive stress. However, the focal mechanism for the Mulga Park earthquake suggests strike-slip failure, with a sub-vertical northerly-trending nodal plane favoured as the failure plane, in contrast to the thrust mechanism for the 2012 event.

Despite being felt more widely than the 2012 event, ground cracking and minor dune settlement were the only surface expressions relating to the Mulga Park earthquake. No vertical displacements were evident, nor were patterns indicative of significant lateral displacement. An 18 km long north to north east trending arcuate band of moderate to high cracking density was mapped parallel to the surface trace of the Woodroffe Thrust, a major crust-penetrating fault system. A lobe of high-density cracking ~5 km long, coincident with the calculated epicentral location, extended to the north from the centre of the main arc. We speculate that the rupture progressed to the south beneath the northern high-density lobe (consistent with the dimensions expected from new scaling relations), and that the larger arcuate band of cracking might relate to positive interference resulting from reflection of

energy from the Woodroffe Thrust interface. Both events provide new insight into the rupture behaviour of faults in non-extended cratonic crust.

Geomorphic and Geologic Evidence of Recently Active Faults and Folds in Java, Indonesia

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Java is a highly populated island in Indonesia along the Sunda-Banda subduction system. There have been damaging earthquakes in Java; however, detailed neotectonic studies are limited. In this study, we present detailed maps of active faults derived from satellite and field-based neotectonic mapping, paleoseismic data, as well as new data on fault kinematics, tectonic geomorphology indices indicating relative rock uplift, and estimates of principal stress orientations from volcano morphology. The structures in East Java are dominated by NW-SE normal faults, Central Java by E-W folds and thrust faults, while NE-SW strike-slip faults dominate West Java. Our preliminary mapping indicates no large scale continuous structures in Java. Instead deformation is distributed over broad areas along small structures. We illustrate our results with examples from the many active structures identified in this study: the Baluran and Pasuruan normal faults in East Java, the Kendeng fold and thrust belt in Central Java, and the Cimandiri strike-slip fault system in West Java. In Pasuruan, two shallow trenches cut across the NW-SE scarp exposed faulted and folded alluvial and colluvial strata and provide evidence for at least three ground-rupturing earthquakes. Uplifted meanders and terraces indicate ongoing uplift along the Kendeng fold and thrust belt. In Cimandiri, the normalized channel steepness index delineates the active trace along the otherwise diffuse fault zone. The structure mapping and principal stress orientations from volcano morphology suggest that the distinctive patterns are likely controlled by inherited crustal structures and variable boundary stresses from subduction of bathymetric highs and angle of the subducting slab. Javan seismic hazards include great tsunamigenic earthquakes along the subduction interface to the south as well as M6-7, widely-distributed shallow earthquakes associated with upper plate structures.

The Timing of the Recent Two Faulting Events on the Himalayan Frontal Fault in Ramnagar Area, Uttarakhand, India

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The Himalayan frontal fault east of Ramnagar in Uttarakhand, India (around 79.2 degree E) is an ideal site for paleoseismological investigation. It is because of a low fluvial energy condition along the frontal fault owing to the separation from large rivers by a growing anticline to the north. We opened a trench in east of Ramnagar at N29.34 d and E79.17 at the tow of 12 m high fault scarp deforming the youngest fluvial terrace on the anticline. The master thrust fault appeared on the trench wall to reach to the last event horizon under the very bottom of the slope. The hanging wall above 11 degree dipping thrust plane is composed of the terrace deposits and folded recumbently. The footwall is composed of massive fine alluvial sand and silt of back marshes. The lowest exposed potion of the footwall is dipping ~15 degrees to the south and contains isolated cobbles and boulders. There is an angular unconformity between the upper and lower portion of the footwall sediments. This is the horizon of the penultimate event. Preliminary radiocarbon dating results indicate the last event occurred after 1246–1383 AD and before 1550–1630 AD, coinciding with the historic 1505 earthquake. A date of the upper alluvial sediments above the horizon of the penultimate event is 56–217 AD. This gives an interval longer than 1300 years and is possibly of a piece of reworked charcoal. Further datings are under way. The slip observed in the trench is larger than 6 m. Kumar et al. (2006) opened a trench about 7 km east of our site and identified the last event before 1433 AD with estimated 26 m coseismic slip. However, the trench did not expose the master fault but only secondary superficial ruptures. As to the large coseismic slip, there is no evidence to interpret the 13 m high scarp as a single-event scarp. Therefore, our new event chronology and slip estimation do not contradict with the observation of Kumar et al. (2006).

New Paleoseismic Study of the Septentrional Fault, Dominican Republic

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The Septentrional Fault is one of two major strike-slip faults that accommodate motion between the Caribbean and North American plates at the longitude of Hispaniola. Earlier paleoseismic work (Prentice, et al., 1993; 2003) showed that east of Santiago, Dominican Republic, the most recent earthquake with surface rupture (MRE) on this fault occurred more than 800 years ago. However, recent analysis of the historical record by ten Brink et al. (2011) concluded that earthquakes in 1842 and 1562 both ruptured the Septentrional Fault across the island. We excavated two trenches at Santiago Viejo, the site of an early European settlement about 1 km northwest of Santiago. The Spanish established the settlement in 1508, and abandoned the site and moved the city after the 1562 earthquake. While the fault traverses the site, there is no evidence among the ruins for historical surface rupture; no colonial ruins are offset, and the scarp itself is degraded by erosion, with no evidence suggesting historical slip. We excavated two trenches across the fault zone to determine if either historical earthquake was associated with surface rupture at this site. Both trenches exposed the fault zone overlain by an unfaulted cultural horizon (defined by the presence of artifacts from the Spanish settlers), suggesting that the MRE occurred prior to European settlement. Radiocarbon dating of charcoal samples collected from post-faulting sedimentary horizons show that the MRE pre-dates the 1842 earthquake, and likely also pre-dates the 1562 earthquake. These results indicate that if 1842 surface rupture occurred on the Septentrional Fault, it occurred on the segment of the fault west of this site. Our preliminary results show no evidence for surface rupture in 1562, but do not entirely exclude it. Current data suggest an age older than 1562 for the MRE. We anticipate that forthcoming radiocarbon and pollen analyses will better constrain the age of the MRE at the Santiago Viejo site.

Revised Earthquake Hazard of the Hat Creek Fault, Northern California: Paleoseismology in Pleistocene Lava Flows

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Normal faults in basalt have distinctive surface-trace morphologies where they cut through near-surface lavas, providing information about slip history and earthquake hazards. Such faults may remain active during prolonged volcanic periods such that different ages of lava flows cut by the fault can be used as temporal markers of slip rates and slip history. The 47-km-long Hat Creek fault in northern California is a case example of this fault style. We address segment evolution, slip history, and earthquake potential based on surface morphologies and throw distribution in variable-aged lavas. In response to interaction with sporadically active volcanic systems, surface ruptures progressively migrated westward in the Late Pleistocene, with older scarps being successively abandoned. The most recent earthquake activity dissects 24 ± 6 ka basaltic lavas, forming a vertical scarp with a maximum throw of 56 m. Other lavas cut by the fault have ages of 38 ± 7 ka and 53.5 ± 2 ka. Prior to surface rupture, the fault formed a fault-trace monocline that attained a height of up to 33 m. Subsequent earthquake activity reduced the monocline to a rubble pile along the fault trace. Dislodged small columns thrown up onto the lava surface suggest >1 g_n acceleration at the surface rupture location. We show that the length of the most recently active portion of the segmented system, which was suggested in past work to be 23.5 km, is actually comprised of at least 9 segments with a cumulative length of 30 km, thus increasing the potential regional seismic hazard. We estimate that a surface-breaking rupture could produce an earthquake of $\sim M_w$ 6.7 with a recurrence interval of 667 ± 167 yr in response to a rapid slip rate in the range 2.2–3.6 mm/yr. This implies a moderate risk given a lack of earthquake events in the past 200 yrs. Our methods for interpreting scarp geomorphology and slip history in faulted lava flows can be applied to any faulted basalt environment.

A Candidate Fault Scarp from the 1872 Earthquake near Chelan, Washington

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The largest historical earthquake in eastern Washington occurred on 15 December 1872 with an epicenter near the south end of Lake Chelan and an estimated moment magnitude of 6.5–7.0 (Bakun et al., 2002). An enduring geologic problem is the lack of surface deformation associated with this earthquake, suggesting the earthquake

occurred on a blind structure or a deep source. Focal mechanisms from recent earthquakes in the area are consistent with regional N-S shortening inferred from GPS studies. Analysis of regional aeromagnetic anomalies show two main lineament orientations; NW-trending lineaments follow the main geologic structures in the area, and NE-trending lineaments extend from rocks on the east flanks of the Cascade Mountains eastward beneath Miocene flood basalts.

New LiDAR data reveal a NW-side-up scarp west of the Columbia River along the north side of Spencer Canyon, 30 km SW of Chelan, WA. The NE-trending scarp is ~5.5 km long, and has a maximum height of 2.4 m. Three-point solutions from measurements using LiDAR data suggest a fault plane striking 250° and dipping between 20–37° NW. These results, coupled with the sense of motion, suggest that thrust motion on a NW-dipping fault created the scarp.

Landslides observed on LiDAR images obliterate the scarp in places, and impound two small ponds. Tree-ring counts of Ponderosa pine ($n = 49$) growing on both landslides establish a minimum age for the scarp – the oldest sampled trees on each landslide are 130 and 128 years old. Wood from a dead tree in one pond yields a 14C age of 130 ± 30 yr BP. The tree ring counts and 14C age suggest that the landslides occurred at about the same time as the 1872 earthquake. Future trenching aims to establish limiting maximum ages for fault movement.

Bakun, W., Haugerud, R., Hopper, M., and Ludwin, R., 2002, The December 1872 Washington State earthquake: Bulletin of the Seismological Society of America, v. 92, p. 3239–3358.

Challenges and Opportunities in Synthesizing Multiple Paleoseismic Data Sets

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As the quantity and quality of paleoseismic records have increased, attention has grown on methods of synthesizing site records into histories of ground rupture on faults and in regions. Paleoseismic trenching provides the 'where' of rupture on a fault, but is rarely precise about the 'when'. Thus even the simplest form of multiple-site synthesis, correlation of events between sites on a fault, has taken the form of scenarios consistent with the dating uncertainty. We look briefly at the difficulties of temporal correlation, and then at ways to link paleoseismic records and to apply them in hazard estimation by bringing in other information. For example, the size of an event displacement at a site should scale with the probability that the event would be detected at some distance down the fault. This approach can be generalized to construct a likelihood grid in time and space for a fault, showing where and where events have been more or less likely in the past. At a higher level one may interpret temporal overlap just as permitting correlation, then bring in outside constraints such as an average slip rate and total number of events. The 'stringing pearls' approach of Biasi and Weldon, used in UCERF2 for the southern San Andreas fault, uses these constraints to estimate rates of events of various sizes, and thus net fault hazard, without having to resolve exact correlations among sites. In a related approach, the UCERF3 project used paleoseismic event rate estimates, ignoring their dates, as one constraint in a generalized inversion for rupture rates and sizes. Finally an areal or systems synthesis of paleoseismic site records strongly suggests that California's main faults rupture with a resolvable degree of time dependence. This systems-level deduction from paleoseismology was independently derived by the UCERF3 project, which found that some form of characteristic behavior is required to fit the slip rate and recurrence data in California.

A Decade of Great Subduction Earthquakes – What Have We Learned From Their Ground-Motions?

Oral Session · Friday · 8:30 AM · 2 May · Room 4 Session
Chairs: Trevor Allen and Gail Atkinson

Ground-Motion Prediction Equations for Large Interface Earthquakes based on Empirical Data from the 2011 M9.0 Tohoku, Earthquake

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Ground motion prediction equations have a major impact on seismic hazard estimates because they control the predicted amplitudes of ground shaking. The modeling and understanding of ground-motion amplitudes due to mega-thrust earthquakes in subduction zones has been hampered by a paucity of empirical ground-motion data for the very large magnitudes of most interest to hazard analysis. Data from the Tohoku M9 2011 earthquake are important in this regard, as this is the largest well-recorded subduction event, and the only such event with sufficient data to enable a clear separation of the overall source, path and site effects. In this study, we use strong-ground-motion records from the M9 Tohoku event to derive an event-specific GMPE. We then extend this M9 GMPE to represent the shaking from other M>7 interface events in Japan by adjusting the source term. We focus on events in Japan to reduce ambiguity that results when combining data in different regions having different source, path and site effect attributes. Source terms (the average residuals of ground-motions with respect to the Tohoku GMPE) scale most steeply with magnitude at the lower frequencies; this is in accord with expectations based on overall source-scaling concepts. Interpolating source terms over the magnitude range of 7 to 9, we produce a GMPE for large interface events of M7 to M9, for NEHRP B/C boundary site conditions in both fore-arc and back-arc regions of Japan. We show how these equations may be adjusted to account for the deeper soil profiles (for the same value of V_{S30}) in western North America, and demonstrate the importance of considering the variability in site conditions when translating ground-motions from one region to another. For the Cascadia subduction zone, the proposed GMPE predicts lower motions at very long periods, higher motions at short periods, and similar motions at intermediate periods, relative to the simulation-based GMPE model of Atkinson and Macias (2009).

Magnitude Scaling Rates for Large Earthquakes in Ground Motion Prediction Equations for Japan

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The Mw=9.0 subduction earthquake in 2011 in Japan provides an invaluable set of strong motion records from K-net and Kik-net in Japan. Together with records from other large earthquakes in Japan, it is possible to systematically investigate magnitude scaling for large earthquakes in a ground motion prediction equation (GMPE) model. We assembled over 15000 high-quality strong motion records from 315 earthquakes with a moment magnitude of 5.0 or larger in Japan. Firstly we classified these events into shallow crustal, upper mantle, subduction interface and subduction slab categories, using hypocenters determined by a number of seismological organizations and a subduction interface geometry model from USGS (Slab1.0). We also developed a set models for site amplification ratios accounting for soil nonlinear response based on 1-D numerical modeling, and we adjusted the numerical model by amplification ratios derived from strong-motion records. For shallow crustal category, we used world-wide records from events with an Mw of 7.0 or larger. For geometric attenuation functions we used continuous multi-segments linear models in natural logarithm forms to model possible multiple reflections and constructive interference among seismic waves traveling at different paths. For magnitude scaling functions, we used two continuous segments hinged at Mw=7.1, a linear and a quadratic magnitude scaling for events with an Mw=7.1 or less, and a linear scaling for events with an Mw>7.1. We found that the effect of magnitude for large events is considerably smaller than that for moderate and moderately large earthquakes from all tectonic locations, consistent with the results from our previous studies. For crustal earthquakes, the magnitude scaling rate for event with an Mw larger than 7.1 is nearly zero at short periods and small or negative for other spectral periods up to 5.0s. For subduction earthquakes, the magnitude scaling rates for Mw>7.1 vary between 30–60% of the

Broadband Synthetic Seismograms for M9 Cascadia Earthquakes Using 3D Simulations

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We are producing broadband (0–10 Hz) synthetic seismograms of M9 earthquakes on the Cascadia subduction zone (CSZ) for various rupture scenarios. At long periods (> 2 s) we are using synthetics from 3D finite-difference simulations for the region west of the Cascade Mountains and extending the 1100 km length of the CSZ. This 3D velocity model includes the dipping subducted plate and sedimentary basins, such as the Seattle, Tacoma, Portland, and Tualatin basins. We use earthquake slip models consisting of two parts: (1) random slip with a large correlation distance (about 100 km) and a specified wave number spectrum and (2) discrete asperities with high stress drops and short rise times of slip. For the first part of the model, an average slip velocity was specified to determine rise times of slip on the fault. The slip velocity was calibrated by comparing response spectral values of synthetics for the M8.8 Maule, Chile earthquake with the observed values. At short periods (<2 s) we use a summation of stochastic seismograms from point sources. The short and long-period synthetics are combined using matched filters. We constrained the stress drop of the discrete asperities for the Cascadia simulations by modeling the observed spectral accelerations and waveforms of the M9.0 Tohoku, Japan earthquake and the

Maule earthquake. For the Tohoku earthquake, the observed spectral accelerations from 10 s to 0.1 s can be explained by high stress drop sub-events located in the deeper portion of the rupture zone. The Maule earthquake consisted of at least three sub-events with high stress drops. We are comparing the spectral accelerations from the Cascadia synthetics with ground-motion prediction equations used in seismic hazard assessments. The synthetics exhibit large amplification of spectral accelerations at 3–5 s by the Seattle basin.

Broadband Strong Motion Simulations of Large Subduction Earthquakes

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The great subduction earthquakes that occurred recently in Peru, Chile and Japan have provided unparalleled information about the ground motions stemming from such earthquakes. Broadband ground motion simulations can enhance the usefulness of the recordings of these earthquakes by providing a means of interpolating and extrapolating the recorded data. In this study, we test our capability to simulate, with a hybrid method, broadband strong motion recordings of mega-thrust earthquakes by demonstrating that our simulations reproduce the amplitudes of the recorded ground motions without systematic bias. The broadband ground-motion simulation method that we used is based on the work of Somerville et al. (1991), Somerville (1993) and Graves and Pitarka (2004; 2010). It computes the long and short period ranges separately and then combines the two to produce a single time history using appropriate matching filters. At periods longer than 1s, the methodology is deterministic and contains a theoretically rigorous representation of fault rupture and wave propagation effects. At periods shorter than 1s, it uses an empirical representation of source radiation and scattering derived from the recordings of a smaller earthquake, which is combined with a simplified theoretical representation of wave propagation. The simulations have a model bias that is generally within 20% of zero across the full bandwidth. A systematic underprediction can be observed around the period of 0.5s. This underprediction could be driven by the characteristics of the empirical source function used in the high frequency part of the simulations. The standard deviation is comparable with the standard deviations of the most recent GMPE models (Zhao et al., 2006:Zea06 and Abrahamson et al., 2012:AGA12). The Atkinson and Boore (2003) (AB03) standard deviation is at the lower bound of the standard deviations from the simulations, while the Zea06 model has very comparable values across the examined period range.

NGA-Sub: Plan to Develop Next Generation Ground Motion Models for Subduction Earthquakes

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The NGA-Sub project is a large multidisciplinary, multi-year research program on the Next Generation Attenuation models for subduction earthquakes. The research project has been coordinated by the Pacific Earthquake Engineering Research Center (PEER) with strong interactions with international organizations. The first step in the NGA-Sub project is to develop an extensive database of ground motions recorded in subduction events worldwide. At this point, thousands of ground motion recordings have been collected and processed. An overview of the NGA-Sub database will be presented along with the plan to develop ground motion prediction equations for subduction events.

75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding

Oral Session · Friday · 10:45 AM · 2 May · Room 4 Session
Chairs: Thessa Tormann, Max Wyss and Jeanne Hardebeck

***b*-Values, Stress and Fault Heterogeneity During Laboratory Stick-Slip Experiments**

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Differences in crustal conditions and faulting mechanisms may lead to regional variations in the frequency-magnitude distributions (FMDs) of crustal seismicity. To better asses controlling parameters of variations in FMDs and *b*-values, we examine fault structure, stress and micro-seismic events during sequences of stick-slip events, a laboratory analog to earthquakes. The experiments were conducted on faults that developed from fresh fracture surfaces in Westerly granite. Our experiments revealed many similarities between laboratory and crustal faults, i.e., a hierarchical damage structure, fractal fault roughness that controls the spatial distribution of seismic events, Omori-Utsu aftershock decays and Gutenberg-Richter type frequency-magnitude distributions. The latter can be described by a powerlaw with an exponent (*b*-value) that varied between 0.7 to 2.2. We analyzed variations in *b*-value along fault strike and as function of differential stress. *b*-values are generally low in regions of relatively thin fault zone width, i.e. little to no gouge content between host-rock walls. These regions also show high seismic moment release and seismic event densities during the inter-slip periods and mark the nucleation sites of stick-slip events. Furthermore, *b*-values decreased systematically with increasing differential stresses during several stick-slip cycles so that seismic events are more likely to grow to larger sizes if ambient stresses are high. In addition, variations in *b*-values are sensitive to the structural complexity of faults observed in post-experimental CT-scans so that less complex faults and faults with larger displacements exhibit a stronger correlation between differential stress and *b*-values. Our results highlight the role of both fault heterogeneity and differential stress in controlling frequency-magnitude distributions during the faulting of rock samples in the laboratory.

Growing Large Scale Fractures in a Salt Mine and their Effects on the Frequency-Magnitude Distribution

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The spatiotemporal seismicity of a massive acoustic emission (AE) catalog recorded in the Morsleben salt mine is here investigated. We first summarize different approaches we have recently proposed to assess the catalogue completeness in strongly heterogeneous media and mining environments. The analysis of complete catalogue and the spatiotemporal distribution of the AE activity present characteristic signatures and the frequency-magnitude distribution locally deviates from the Gutenberg-Richter law. Almost a year after backfilling of the cavities, microevents are distributed with distinctive stripe shapes above cavities at different depth levels. The physical forces driving the creation of these stripes are still unknown. This study aims to find the active stripes and track fracture developments over time by combining two different temporal and spatial clustering techniques into a single methodological approach. Anomalous seismicity parameters values like sharp b-value changes for two active stripes are good indicators to explain possible stress accumulation at the stripe tips. We identify the formation of two new seismicity stripes and show that the AE activities in active clusters are migrated mostly unidirectional to eastward and upward. This indicates that the growth of underlying macrofractures is controlled by the gradient of extensional stress. Studying size distribution characteristic in terms of frequency-magnitude distribution and b-value in active phase and phase with constant seismicity rate show that deviations from the Gutenberg–Richter power law can be explained by the inclusion of different activity phases: (1) the inactive period before the formation of macrofractures, which is characterized by a deficit of larger events (higher b-values) and (2) the period of fracture growth characterized by the occurrence of larger events (smaller b-values).

Geomechanical Modeling of Frequency-Magnitude Distributions of Induced Seismicity

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Induced seismicity from different sources is becoming more and more a public concern. The largest events in the recent past came from wastewater injections and geothermal heat extraction. In the future, Carbon Capture and Storage is believed to be an additional source. To understand the ongoing processes better, seismicity has to be monitored with a dense local network, including borehole stations in the

best case. The evolution of the seismic cloud indicates the location of the injected fluid in the ground. While this is crucial to know for geothermal heat extraction, as the water will be extracted through a second borehole, it is also important for the understanding and analysis of the other processes.

To better predict size distributions of the induced seismic events, we introduce a geomechanical model, simulating the pore pressure diffusion in the media. We relate the induced event-sizes to the differential stress via an empirical inverse relationship, established from tectonic events and laboratory experiments. With this simplistic model, we can reproduce the frequency-magnitude distributions found from injection experiments, such as the Enhanced Geothermal System in Basel, Switzerland and a long-term brine injection in Paradox Valley, Colorado. We find significant temporal and spatial changes in the b-value of those injections; highest values are found closest to the injection points and earliest during the injection. Our model allows us to relate those changes to the pore pressure changes. We conclude that highest pore pressure changes lead to high b-values as those induce events with smaller sizes. We are therefore able to establish a link between the seismological observables and the geomechanical properties of the source region and thus a reservoir. Understanding the geomechanical properties is essential for estimating the probability of exceeding a certain magnitude value in the induced seismicity and hence the associated seismic hazard of the operation.

Tectonic b-Value Variation Interpreted as Stress-Meter – Examples from Different Scales

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The slope of the frequency magnitude distribution of earthquakes, characterized by the Gutenberg-Richter b-value, has been observed to vary through space and time on various scales. An early suggested interpretation is a negative dependence of b on differential stress, as has been observed in laboratory experiments. High b-values, describing a sample with a high proportion of small compared to large magnitudes, correspond to low stress, while high stress conditions produce a higher proportion of large magnitudes and a low b-value.

Generic b-value depth gradients reflect the strength gradient of the brittle crust. Localized b-value patterns along faults have been successfully related to future and past ruptures on known and previously unknown asperities. Distinct high b-value volumes beneath volcanoes have been related to the high pore-pressure environment of magma bodies. Imaging b-values along subduction zones, e.g. the Pacific plate off and beneath Japan, reveals a striking footprint of the tectonic structures. Temporal changes of b-values within selected structures are consistent with loading and unloading of asperities.

The presentation shows a variety of independent observations of b-value features that are consistent with the stress correlation hypothesis and suggest that b-values are indeed physically rooted and can be used to image relative crustal stress conditions.

Local Magnitude Distributions in the 3rd Uniform California Earthquake Rupture Forecast (UCERF3)

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Rather than the prescriptive approaches used to define rupture rates in hazard models of the past, the 3rd Uniform California Earthquake Rupture Forecast (UCERF3) uses an inversion method to derive rupture rates consistent with fault slip rates, paleoseismic data, and regional seismicity rates. The inversion method allows us to probe which hypotheses are consistent with the model parameterization and input data. We were unable to construct a model that imposed a Gutenberg-Richter magnitude distribution on the major faults in California. This is because such a model cannot put enough moment on the faults to match the target slip rates without a) assuming significantly more fault connectivity and therefore raising the maximum magnitude, b) over-predicting historically observed seismicity rates, and/or c) introducing significant b-value variation by lowering the b-value on major faults. We present evidence for some of these potential 'fixes' which could make the Gutenberg-Richter branch tractable, but possibly not to the extent they would be needed. Interestingly, UCERF3 is significantly less 'characteristic' than UCERF2, both statewide (where rates are constrained to match the Gutenberg-Richter distribution) and in smaller regions, due to the relaxation of segmentation and inclusion of multi-fault ruptures.

Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario - Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation

Oral Session · Friday · 1:30 PM · 2 May · Room 4 Session Chairs: Elena Suleimani, Stephanie Ross, Hong Kie Thio, and Dmitry Nicolsky

Far-Field Tsunami Detection and Warning, 1854–2014: One Hundred and Sixty Years in the Intricate Relation between Earthquake Source and Tsunami

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The first scientific study of a tsunami as generated by a distant earthquake can be traced to Bache [1856] who correctly identified waves from the 1854 Nankai earthquake on California tidal gauges. We will review developments in the study of the relationship between earthquake source and far field tsunami, with their logical application to distant warning.

Among the principal milestones, we discuss Hochstetter's [1869] work on the 1868 Arica tsunami, Jaggar's real-time, but ignored, warning of the 1923 Kamchatka tsunami in Hawaii, his much greater success with the 1933 Showa Sanriku event, the catastrophic 1946 Aleutian event, which led to the implementation of PTWC, the 1960 events in Hilo, and the 1964 Alaska tsunami, which led to the development of the A[now N]TWC.

From the scientific standpoint, we will review the evolution of our attempts to measure the seismic source (in practice its seismic moment), always faster, and at always lower frequencies, culminating in the W-phase inversion, heralded by Kanamori and co-workers in the wake of the Sumatra disaster. Specific problems arise from events violating scaling laws, such as the so-called "tsunami earthquakes", and we will review methodologies to recognize them in real time, such as energy-to-moment ratios. Finally, we will discuss briefly modern technologies aimed at directly detecting the tsunami independently of the seismic source.

Tsunami Modeling and Inundation Mapping in Southcentral Alaska

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The Alaska Earthquake Center (AEC) participates in the National Tsunami Hazard Mitigation Program by evaluating and mapping potential tsunami inundation of coastal Alaska.

We evaluate potential tsunami hazards for several coastal communities near the epicenter of the 1964 Great Alaska Earthquake and numerically model the extent of their inundation due to tsunamis generated by earthquake and landslide sources. Tsunami scenarios include a repeat of the tsunami triggered by the 1964 Great Alaska Earthquake, as well as hypothetical tsunamis generated by 1964-type ruptures, a Cascadia megathrust earthquake, and a hypothetical Tohoku-type rupture in the Gulf of Alaska region. Local underwater landslide events in several communities are also considered as credible tsunamigenic scenarios. We perform simulations for each of the source scenarios using AEC's recently developed and tested numerical model of tsunami wave propagation and runup. The tsunami scenarios are intended to provide guidance to local emergency management agencies in tsunami hazard assessment, evacuation planning, and public education for reducing future casualties and damage from tsunamis.

During the 1964 earthquake, locally generated waves of unknown origin were identified at several communities, located in the western part of Prince William Sound. The waves appeared shortly after the shaking began and swept away most of the buildings while the shaking continued. We model the tectonic tsunami assuming different tsunami generation processes and claim the importance of including both vertical and horizontal displacement into the 1964 tsunami generation process.

Inundation Mapping and Hazard Assessment of Tectonic and Landslide Tsunamis in Southeast Alaska

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The Alaska Earthquake Center conducts tsunami inundation mapping for coastal communities in Alaska, and is currently focused on the southeastern region. This activity provides local emergency officials with tsunami hazard assessment, planning, and mitigation tools. At-risk communities are distributed along several segments of the Alaska coastline, each having a unique seismic history and potential tsunami hazard. Thus, a critical component of our project is accurate identification and characterization of potential tectonic and landslide tsunami sources. The primary tectonic element of Southeast Alaska is the Fairweather – Queen Charlotte fault system, which has ruptured in 5 large strike-slip earthquakes in the past 100 years. The 1958 "Lituya Bay" earthquake triggered a large landslide into Lituya Bay that generated a 540-m-high wave. The M7.7 Haida Gwaii earthquake of October 28, 2012 occurred along the same fault, but was associated with dominantly vertical motion, generating a local tsunami. Communities in Southeast Alaska are also vulnerable to hazards related to locally generated waves, due to proximity of communities to landslide-prone fjords and frequent earthquakes. The primary mechanisms for local tsunami generation are failure of steep rock slopes due to relaxation of internal stresses after deglaciation, and failure of thick unconsolidated sediments accumulated on underwater delta fronts at river mouths. We numerically model potential tsunami waves and inundation extent that may result from future hypothetical far- and near-field earthquakes and landslides. We perform simulations for each source scenario using AEIC's numerical model of tsunami propagation and runup, which is validated through a set of analytical benchmarks and tested against laboratory and field data. Results of numerical modeling combined with historical observations are compiled on inundation maps and used for site-specific tsunami hazard assessment by local emergency planners.

The SAFRR Tsunami Scenario: Improving Resilience for California from a Plausible M9.1 Earthquake near the Alaska Peninsula

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The SAFRR Tsunami Scenario models a hypothetical but plausible tsunami, created by an Mw9.1 earthquake occurring offshore from the Alaska Peninsula, and its impacts on the California coast. We present the likely inundation areas, current velocities in key ports and harbors, physical damage and repair costs, economic consequences, environmental impacts, social vulnerability, emergency management, and policy implications for California associated with the tsunami scenario.

In this scenario, approximately three-quarters of a million people could be ordered to evacuate from residences, businesses, public venues, parks and beaches. Some island and peninsula communities would face evacuation challenges. One third of the boats and over half of the docks in California's marinas would be damaged, sunk or destroyed. Fires would likely start at many sites where fuel and petrochemicals are stored in ports and marinas. Tsunami surges and bores could travel several miles inland up coastal rivers. The ports of Los Angeles and Long Beach would be shut down for a minimum of two days due to strong currents. Debris clean-up and recovery of inundated and damaged areas would take days to years. Total economic losses could range from 5 to 10 billion dollars, depending on business continuity and resilience strategies. These losses include property damage, port shutdowns, and business interruption. Addressing serious issues due to sediment transport and environmental contamination, such as the erosion of contaminated harbor bottom sediments, could increase the costs.

The SAFRR Tsunami Scenario has already yielded two positive outcomes. In areas where the scenario inundation exceeds the State's maximum inundation zone, emergency managers have been notified and evacuation plans have been updated appropriately. The State of California has also worked with NOAA's West Coast and Alaska Tsunami Warning Center to modify message protocols to facilitate effective evacuations in California.

Advances in Tsunami Risk Assessment and Risk Mitigation

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Constructing a disaster scenario forces one to identify all potential damage from the peril in question, suppressing the streetlight effect in which one only looks for knowledge where it is easiest. The SAFRR Tsunami Scenario forced us to evaluate damage to several vulnerable asset classes for which tsunami risk models are sparse, especially coastal marinas, ports, bridge abutments, roadways, and to some extent coastal buildings. Scenario development brought to light several analysis and design needs. First, the American Society of Civil Engineers publishes design guidelines for small-craft harbors, which state that because "the frequency of occurrence of a tsunami at any location is very small, small craft harbors do not include design considerations for protection from their appearance." Consequently, pilings in California coastal marinas are too short to restrain floating docks in a reasonably foreseeable tsunami. California coastal ports are similarly exposed to several modes of foreseeable damage. For example, a port dispersal plan created by the US Coast Guard for dispersing the Ports of Los Angeles and Long Beach contains no guidance for decision-making in tsunamis, and there does not appear to be sufficient resources (especially pilots) to disperse vessels in the port within a reasonable tsunami warning time. A modest number of California highway bridges have abutments that intrude into the flow of a tsunami current and could be damaged by scour, and a few stretches of coastal highway are low enough to suffer scour damage in the event of a tsunami, some of them important routes and some of them lacking convenient alternatives during repairs. A large number of coastal buildings—the equivalent of 70,000 single-family dwellings—are close enough to the shore and at low enough elevation to suffer damage in a tsunami. Several modes of damage could be reduced with changes to design guidelines and zoning changes.

Numerical Modeling of the SAFRR Tsunami Scenario

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The SAFRR Tsunami Scenario is a multidisciplinary study of the physical, economic and social impact in California of a large tsunami originating in the Aleutian Islands. The wave modeling was carried out by several teams based on a common rupture model that was developed by the SAFRR working group. Although modeling was carried out for populated areas along the entire California coast, most of the efforts were concentrated on Southern California. We will present an overview of these efforts and the physical impact of the model tsunami on the California coastline. For most populated areas, the tsunami was modeled at resolutions of 30 m but for several areas more focused models were computed at higher resolutions. Because several different approaches were used for both the source characterization as well as the tsunami modeling, this study also gives a good opportunity to evaluate the similarities and differences between the various approaches. Understanding these differences are important for the future evaluation of tsunami hazard, which is invariably based on numerical modeling since it allows us to quantify the uncertainties at the different stages of the process. At the source it will give us insight in alternative ways to translating slip on the fault into initial tsunami amplitudes, and how dynamically derived rupture models compare to simple static/kinematic ones. At the shoreline, the differences between the various modeling algorithms are apparent, and we will evaluate these both in terms of the inherent uncertainty of the tsunami

models as well the effect of different algorithms and grid resolution. We will highlight some of these results for areas in Southern California such as the Ports of Los Angels/Long Beach and San Diego where most of the parallel studies were carried out.

Modeling Megathrust Rupture through Stable-Sliding Zones, and Implications for an Alaskan-Aleutian Megathrust Earthquake and Tsunami

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Motivated by the 2011 M9 Tohoku-Oki event and potential earthquakes on the Alaskan-Aleutian (A-A) Megathrust, we investigate the effects of realistic fault dynamics on slip, free surface deformation, and resulting tsunami formation from an M9 megathrust earthquake. We model three scenarios: a spatially-homogenous prestress and frictional parameter model, and two models with regions of rate-strengthening-like friction (e.g., Dieterich, 1992). We use the dynamic finite element code EQDyna (Duan and Oglesby, 2006) to model 3-D ruptures, using time-weakening friction – a simple slip-weakening-type friction law – as a proxy for rate-strengthening friction, along a portion of the A-A subduction zone. Given geometric, material, and plate-coupling data along the A-A megathrust assembled by the Science Application for Risk Reduction (SAFRR) team (e.g., Bruns et al., 1987; Hayes et al., 2012; Johnson et al., 2004; Santini et al., 2003; Wells at al., 2003), we are able to dynamically model rupture with implications for tsunami generation. Adding frictional-strengthening to a region of the fault reduces both average slip and free surface displacement above the strengthening zone, with the magnitude of the reduction depending on the strengthening zone location. Corresponding tsunami models, which use a finite difference method to solve linear long-wave equations (Shuto, 1991; Satake, 2002), match sea floor displacement, in time, to the free surface displacement from the rupture models. Tsunami models show changes in local peak amplitudes and beaming patterns for each slip distribution. Future work will focus on more realistic fault geometry, stochastic stress distributions, and stochastic frictional-strengthening distributions that match observations.

Incorporating Progressive Rupture into Tsunami Models for Tsunami Warning

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Tsunami warning centers run tsunami models after every potentially tsunamigenic earthquake to determine the region to be warned. Models currently assume instantaneous rupture, but for slow or very large earthquakes that assumption can produce misleading forecasts, particularly if rupture is unilateral. For example, the unilateral rupture of the M7.7 2006 West Java earthquake (rupture speed ~1 km/s), rotated the maximum of the tsunami radiation pattern 13° from the trench-normal maximum implicit in instantaneous rupture. If such a slow earthquake were to occur off the Alaska Peninsula, erroneously assuming instantaneous rupture would result in underwarning for the West Coast and overwarning for Hawaii, or vice versa, depending on the direction of rupture. For the largest earthquakes (which tend to rupture unilaterally) the consequences of mismodeling are even more severe. Runup on the coasts of Sri Lanka and India during the 2004 Indian Ocean tsunami cannot be explained without invoking progressive south-to-north rupture of the Sumatra-Andaman earthquake, and the errors of the instantaneous model progressively grow as calculations are carried into Atlantic and Pacific Oceans. To avoid such problems, we are developing a fast finite-fault analysis procedure to define the propagating-rupture sources needed for tsunami modeling. Until this procedure is implemented, however, we shall have to assemble ad hoc progressive-rupture sources guided by the mismatch between hypocenter and centroid locations (the latter determined from W-phase inversions) and between origin time and centroid time.

Joint Earthquake Source Inversion of Land- and Ocean-based Geophysical Sensors for Tsunami Early Warning

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Computation of tsunami intensities in the regions adjacent to large earthquakes immediately after rupture remains a challenging problem. Seismological instrumentation in the near field cannot be objectively employed for real-time inversions and the non-unique source inversion results are a major concern for modelers. Employing near-field seismic, GPS and ocean wave gauge data from the M9 Tohoku-oki earthquake, we test the capacity of static finite fault models to produce reliable tsunami forecasts. We demonstrate the ability of seismogeodetic source models determined from combined land-based GPS and strong motion seismometers to forecast near-source tsunamis in ~3 minutes after origin time (OT). We show that these models, based on land-borne sensors tend to underestimate the tsunami but are good enough to provide a realistic first warning. We show that rapid ingestion of offshore shallow water (100–1000 m) wave gauge data significantly improves the model forecasts and possible warnings. We ingest data from ocean-bottom pressure sensors and GPS buoys into the inversion process. Tsunami Green functions are generated using the GeoClaw package, a benchmarked finite volume code with adaptive mesh refinement. These are used for a joint inversion with the land-based data and substantially improve the earthquake source and tsunami forecast. Model skill is assessed by detailed comparisons of the simulation output to 2000+ tsunami runup survey measurements collected after the event. We update the source model and tsunami forecast at 10 min intervals. By 20 min after OT the tsunami is well-predicted with a high variance reduction to the survey data and by ~30 minutes a final model is obtained with little changed observed afterwards. This approach minimizes operator interaction, it relies on a finite-extent CMT to distinguish among strike-slip, normal and thrust faulting events, all of which have been observed in subduction zones. and pose distinct hazards.

Meteotsunamis Generated by Mesoscale Convective Systems along the U.S. East Coast on June 13th, 2013

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Two high-frequency sea level oscillation events occurred on June 13th, 2013 along the east coast of the United States, causing injuries and property damages. No earthquakes or other known geologic triggers were detected near the coast at the time of the events. However, the events coincided with the passage of two eastward propagating mesoscale convective systems (MCSs) that produced high-frequency atmospheric surface pressure anomalies. While the MCSs were over land, the USArray Transportable Array recorded the associated pressure anomalies in detail; as the pressure anomalies moved offshore, they were recorded by NOAA tide gauge sensors. As the MCSs propagated over the ocean, the pressure anomalies generated shallow water waves, which were amplified by Proudman resonance under an approximately Froude number one regime. Analysis of the NOAA tidal data reveals that after the atmospheric forcing is negligible, these shallow water waves (i.e. meteotsunamis) propagated freely, reflected off the continental shelf break, and arrived at various coastal locations, where the local bathymetry and coastal geometry contributed to the meteotsunamis' destructive impacts. This case study demonstrates that it is possible and perhaps advisable to quantify pressure anomalies associated with MCSs in the interior of the continental United States, which could lead to real-time prediction of MCS-generated meteotsunamis and set the stage for a meteotsunami warning system.

Tracking Fluid Movement in Volcanic Systems

Oral Session · Friday · 8:30 AM · 2 May · Room 7/8 Session Chairs: John Lyons, Helena Buurman, Diana Roman and David Fee

Re-Examining the Tectonic/Magmatic Controls on Dynamic Triggering in the Brittle Crust

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Theoretical considerations suggest that transtensional environments may be more likely to experience dynamic earthquake triggering than transpressional environments. This conclusion assumes optimally oriented faults, Anderson faulting theory, and that Coulomb failure is at play. However in some locales, including volcanic regimes, the factors controlling rupture initiation may be more complicated. It has been suggested that volcanoes are unusually susceptible to triggering due to high heat flow, high pore-fluid pressures, and dynamic fluid migration. To probe this issue, we assess dynamic triggering and lack thereof at 24 seismically monitored Alaskan volcanoes. Since these volcanoes have a wide range of seismicity and stressing rates, both spatially and temporally, as a group they provide a comprehensive perspective on the likelihood of dynamic triggering in active volcanic regimes. The time period of our study (2006–2013) includes six eruptions at five volcanoes and several non-eruptive magmatic intrusions. We find that clear evidence of immediate dynamic triggering is lacking after 48 M7+ events in all but two cases: Pavlof Volcano following the 2011 M9.0 Tohoku-Oki earthquake and Martin Volcano following the 2007 M8.1 Kurile earthquake. In the Pavlof case the long-period nature of triggered events suggests that disruption of the hydrothermal or magmatic system

may be the culprit process. Delayed dynamic triggering is more common at several additional volcanoes and geothermal systems, also suggesting an aseismic root to the triggering process. Overall, however, dynamic earthquake triggering at Alaskan (and reportedly Japanese) volcanoes is rare compared to some areas such as the western contiguous United States, even during times of intense volcanic unrest.

Magmatic and Hytrothermal Fluid Controls on Deep, Distal and Shallow Volcanic Seismicity

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We present evidence that magmatic fluids primarily drive six types of seismicity at volcanoes: 1) deep, primarily low-frequency (DLF) seismicity, 2) distal volcano-tectonic (dVT) events, 3) shallow very-low-frequency (VLF) events, 4) shallow low-frequency (LF) seismicity, 5) spasmodic bursts of shallow (SBVT) events and 6) very shallow hybrid seismicity. We show that hydrothermal fluids are also involved in generation of seismicity types 2), 4) and 5). Trends precursory to eruptions include DLF (e.g., >15 km deep) seismicity as mafic magma rises through the lower crust and dVT earthquakes as magma rises through the mid-crust. Magma reaching the uppermost crust produces VLF events as magmatic fluids intrude the brittle crust and produce LF and SBVT seismicity as those fluids interact with hydrothermal systems. Finally, very shallow hybrid earthquakes occur as silicic magma rises through the uppermost 1–2 km of the crust. A survey of 78 eruptions at 61 dormant volcanoes shows they were preceded by dVT earthquake swarms on tectonic fault structures 2–30 km away from the intruding magma. This dVT seismicity ramped up over hours to years, then peaked and suddenly died off at the time of initial phreatic explosions. Focal mechanisms of the dVT's have >50% CLVD components and at the time of dVT die-off, extrusions of H2O were often observed as sudden artesian springs and/or lahars. We infer that dVT seismicity is produced when magmatic intrusions over-pressurize confined aquifers driving water into and unlocking adjacent pre-stressed faults. Phreatic explosions then temporarily destroy confinement of the aquifers by boiling off and/or squeezing out the water, terminating the distal seismicity at least temporarily but then initiating LF, VLF and SBVT seismicity as magma rises into the hydrothermal zone. The seismic energy release rates, deformation and gas emissions are correlated and controlled by magma ascent rate and degassing.

Do Pre-Eruptive Swarms have Systematically Different Earthquakes than Non-Eruptive Swarms?

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Almost all volcanic eruptions are preceded by a seismic swarm, but not all seismic swarms precede volcanic eruptions. Swarms that lead to eruptive activity are presumed to be triggered by the ascent of magma through the brittle crust. The triggers for swarms that do not precede eruptions are more varied, and can include the movement of hydrothermal fluids, changes in the regional stress field and surficial processes such as glacial surges or landslides. To complicate things further, deformation data and gas measurements often indicate that swarms which don't erupt are still triggered by ascending magma, but that the rising magma stalls before it reaches the surface. The challenge for volcano seismologists is to identify when a swarm is being generated by rising magma that will lead to an eruption.

In this study we search for correlations within pre-eruptive and non-eruptive swarms from a variety of volcanic settings. In order to make systematic comparisons across our dataset, we employ identical processing techniques to waveform data from over 20 existing earthquake catalogues. We analyse temporal variations in the waveform frequency content and repeatability throughout each swarm in our dataset. Magma intrusions are known to disrupt the local stress field, which affects where seismicity is generated as well as the local attenuation structure. We search for patterns in the hypocenter distribution and the waveform characteristics of pre-eruptive swarms that are not present in other swarms, which can be attributed to the change in the local stress field due to the presence of magma. We also examine whether volcanic setting systematically influences these waveform characteristics.

Short-Term Seismic Quiescence Immediately Preceding Explosive Eruptions

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Vulcanian, phreatic explosions are relatively common at active volcanoes, often occur without obvious warning, and endanger people and/or aircraft in the immediate vicinity of the vent. Thus, identification of subtle short-term precursors to individual phreatic explosions is critical for reduction of local volcanic hazard worldwide. The March-June 2011 eruption of Telica Volcano, Nicaragua, eruption was phreatic or phreato-magmatic, and required the evacuation of over 500 people from the local area. The eruption consisted of numerous small to moderate ash explosions, with the largest occurring between May 13–23. Combined visual, infrasound, and seismic observations indicate a total of 30 explosions during May 2011. Concurrent seismic activity was recorded by a local broadband seismic network (the TESAND network). Comparison of the timing of seismically-detected explosions with seismicity rates indicates that explosions follow short-term periods of reduced seismic activity from May 13–26, and visual inspection of continuous seismic data confirms that explosions from May 13 onwards are preceded by 1–4 hours of dramatically reduced seismicity rates. During May 2011, Telica's seismicity consisted predominantly of low-frequency (LF) events, which may be the result of gas flow through a relatively open shallow hydrothermal system. We suggest that short-term sealing of the shallow hydrothermal system led to the observed precursory cessations of LF seismicity and a build-up of gas pressure leading to the ensuing phreatic explosions. Similar short-term decreases in seismic activity have also been documented prior to explosive eruptions at Suwanose-jima Volcano, Japan, and Redoubt Volcano, Alaska. Thus, it is possible sudden cessation of LF seismicity at an open-vent or restless volcano may function as a short-term warning that an explosion is imminent.

Evidence for Ongoing Magma Recharge at Mount St. Helens, Washington

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Since the last eruption of Mount St. Helens (MSH) in 2004–2008, earthquake rates of $M > 0$ per year have been slightly lower (95 located events per year) than in the five years prior to 2004 (115 per year). This is in marked contrast to the five years immediately following the 1980–86 eruptive period, when the yearly average rate was 400 events and there was clear evidence, in the form of rotated fault-plane solutions (FPS), that magma recharge was occurring at depths > 2 km. However, analysis of 55 FPS from 2008–2013 show that stress fields at depths > 2 km are significantly different from the regional stress field, with most P and T axes quasi-horizontal and on average rotated ~30 degrees. These patterns are broadly consistent with repressurization occurring within the magmatic system. The majority of these FPS come from 2012–2013, when there was also a significant increase in the number of events occurring at depths > 2 km. Additional evidence for recharge comes from deformation trends observed on the GPS network that has been in place at MSH since 2004. Decaying inward and downward motion of nearby GPS stations accompanied the 2004–2008 eruption. This deformation reversed after the eruption stopped in January 2008, eventually recovering about half of the observed deflationary deformation before leveling off in the last several years. Deformation modeling indicates that a deep magma source, best fit by a 7-km-deep vertically elongate prolate spheroid, fed the eruption and was partially recharged in the years after the eruption stopped. Although recharge is indicated by these trends, we infer that the rate of recharge in 2008–2013 is much less than in 1987–1992 based on the lower seismicity rates and seismic moment release.

Volcanic Tremor and Frequency Gliding during the 2011 Kamoamoa Eruption, Kilauea, Hawai'i

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We examine seismic data from 11 stations during the 2011 Kamoamoa eruption (Mar 6–10), Kilauea, Hawai'i. On Mar 6, magma drained from the summit and from Pu'u O'o into an inflating dike in the East Rift Zone (ERZ). The eruption started when the dike reached the surface, and lasted until Mar 10.

Volcanic tremor persisted throughout the eruptive episode with varying amplitudes. At stations closest to the summit, non-harmonic tremor was characterized by oscillation frequencies below 7 Hz, with energy concentrated between 1–2 Hz.

For the first time on Kilauea, we detect a systematic temporal variation in the frequency of a spectral peak (frequency gliding). After the onset of tremor, there was an approximately linear increase in the frequency of a spectral peak from 0.5–6 Hz over several hours, followed about a day later by a similarly linear decrease. We test

whether gliding is related to the filling and draining of the dike through diffusion of pore pressure into the porous rocks of the ERZ.

We assume the rock forming the ERZ is a deformable rock-gas porous matrix. Over the short time scale of the gliding oscillation we assume that the gas is trapped, behaving as a restoring gas spring with a stiffness that depends on pore pressure. Migration of magma from the summit into the ERZ introduces a pressure transient. This drives a pressure wave into the surrounding rocks, where the gas phase oscillates in response to some external forcing. The diffusion of pore pressure causes the gas spring to stiffen and the tremor frequency to climb. Draining of the dike reverses the process, ultimately causing the tremor frequency to decline.

Our model is consistent with visual observations of the eruptive activity during the Kamoamoa eruption. We test the sensitivity of the model predictions to physical parameters and temporal and spatial scales prescribed by the observations, and search for gliding during a previous, similar eruption at Kilauea in 2007.

Air-ground Coupling of Volcanic Tremor Using Cross-Spectral Analysis

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Identification of volcanic activity using geophysical sensors is often difficult due to limited deployments, low signal-to-noise, and complex waveforms. Recent studies have focused on integrating seismic and acoustic sensors to better characterize volcanic activity, including air-ground and ground-air coupling. However, volcanic eruptions often simultaneously generate sustained seismic and infrasonic signals, e.g., by fluid flow occurring in both the subsurface and atmosphere. We employ and build upon the recent work of Ichihara et al. [2012] using cross correlation, coherence, and cross-phase spectra between vertical seismic velocity and acoustic pressure waveforms to provide new information about air-ground and ground-air coupling. We combine this method with infrasound array processing at Mount St. Helens to clearly identify air-ground coupling of acoustic energy previously thought to be seismic tremor. Applying this method to other volcanoes (e.g. Redoubt, Augustine) illustrates some of the limitations and complexities of the method as well. Lastly, we apply the method to the Chelyabinsk meteor signal recorded on the USArray and an IMS infrasound array to show air-ground coupling of this signal is apparent even at long-range and relatively low signal-to-noise. We anticipate this type of analysis will have wide applicability to arbitrary seismo-acoustic sources and in exploiting the growing volume of seismo-acoustic data

Seismic Radiation from Volcanic Conduits: Characterization of Propagating Waves and Source Excitation

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Volcanic conduits are strongly stratified multiphase mixtures of magma, bubbles and crystals exhibiting vertical gradients in density and pressure that drive flow. Perturbations to this system will excite normal modes that would couple to the solid Earth and atmosphere. Waves propagating up and down the conduit provide a potential link between seismic or infrasonic observations and fluid processes that control eruption style and mass discharge. We examine the behavior of such waves in a model of multiphase flow within a cylindrical conduit. Magma is idealized as a mixture of gas and liquid phases, accounting for compressibility of both phases, viscosity of the mixture, and a finite exsolution time for mass exchange between the phases. We study perturbations to a static magma column as well as a case in which there is steady background flow (as during an eruption). In the short-wavelength limit, normal modes of the conduit are characterized by a dispersion relationship with three distinct frequency regimes, in which propagation occurs at the nonequilibrium sound speed of the bubbly fluid, the equilibrium sound speed, and speed of gravity waves. A more general numerical stability analysis, in which perturbations are superimposed on background gradients in base state variables in a finite length conduit, reveals that normal modes are localized as a function of depth. Depending on the degree of stratification (gas content) and presence of background flow, we find modes trapped above and below the gas exsolution depth, as well as above and below the fragmentation depth (for the case of an explosive eruption). In the presence of fluid viscosity and non-equilibrium volatile exsolution, conduit acoustic waves are generally damped, although damping rate varies as a function of wavelength. We are currently studying the excitation of volcanic conduit normal modes by moment tensor sources within the conduit, and will then predict the resulting long period seismic radiation.

Volcanic and Non-Volcanic Events from the Nascent Mt. Pagan Seismo-Acoustic Network

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Mt. Pagan is a small (570 meters above sea level), active basaltic cone filling a caldera that sits atop one of the largest volcanoes (2160 km^3) in the Mariana volcanic arc front, with a base that extends 2000–3000 meters below sea level. A VEI 4 eruption in 1981 that forced the evacuation of the island was the most recent serious activity, but low-level activity is persistent with a robust degassing plume and occasional small ash explosions. A new monitoring network was installed in 2013, consisting of 7 broadband seismometers, 2 6-component infrasound arrays and two web cameras. The activity to date is dominated by frequent long-period (LP) events ($>$ 1000/day) with energy peaked from 0.6–2 Hz. The network has also recorded extended (minutes duration), emergent seismo-acoustic signals likely associated with energetic degassing as well as explosion signals. Continuous beamforming of waveforms from the infrasound arrays shows that degassing from the summit vent is an impressive source of nearly continuous, low-frequency sound. We provide an overview of the signals recorded on the Pagan network since July 2013, including characteristics of repeating LP events and initial location constraints and source mechanisms of seismic events.

In addition to volcanic signals, the network has proven useful for discriminating between volcanic and non-volcanic LP signals. Non-volcanic sources of LP signals generally include ice movement and glacial outburst floods, and the waveform characteristics and frequency content of these events often make them difficult to distinguish from volcanic LP events. We analyze seismic and infrasound data from an LP swarm recorded at Pagan on 12–14 October 2013, and compare the results to ocean wave data from a nearby buoy. We demonstrate that although the events show strong similarity to volcanic LP signals, the events are not volcanic but due to intense surf generated by a passing typhoon.

Cyclic hybrid swarms at Soufriere Hills Volcano, Montserrat, 1996–2001

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Banded tremor is a fascinating signal where cycles of volcanic tremor, comprised of hybrid earthquakes, repeat at intervals of several hours. Banded tremor has been recorded on many volcanoes including Izu-Oshima, Etna, Nevado del Ruiz, St. Helens, Pinatubo and the Soufriere Hills Volcano (SHV), Montserrat. We analyzed 1-minute RSAM and tiltmeter data from Jul 1995 – Dec 2001 to construct a catalog of cyclic seismicity recorded at SHV. We identified 8 episodes of cyclic seismicity, ranging in duration from 1–12 weeks, containing 645 cycles with periods ranging from 3–24 hours and reduced displacement up to 5 cm^2. Comparing our catalog of cyclic seismicity to a catalog of dome collapse events we found 19 of 21 dome collapses during phase 1 of the eruption (Jul 1995-Mar 1998) were preceded by or coincident with (cyclic) swarms. In phase 2 of the eruption (beginning Nov 1999) major dome collapses were instead followed by cyclic seismicity. No cyclic seismicity was recorded during the pause (Mar 1998-Nov 1999).

We suggest that cyclic swarm episodes are a symptom of a high pressure gradient in the magmatic column, caused by either the influx of new magma at depth, or the removal of the dome complex. In phase 1, characterized by rapid extrusion, rapid magma ascent caused frequent small dome collapses and Vulcanian explosions, which terminated or reduced the amplitude of cyclic swarms. In phase 2, characterized by slower extrusion, larger, more stable dome complexes were built. The major dome collapses that occurred depressurized the upper conduit, leading to accelerated magma ascent and onset of cyclic seismicity. Ash venting and dome glow were observed at the peak of many cycles.

Citizen Seismology: Citizens Helping Science Helping Citizens

Oral Session · Friday · 1:30 AM · 2 May · Room 7/8 Session
Chairs: Paul Earle, Susan Hough and Gail Atkinson

Earthquake Intensity Distributions: A New View

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Previous studies have demonstrated both the tremendous value of macroseismic data and the perils of their uncritical assessment. Traditionally, archival accounts of historical earthquakes are used to assign intensity values using the modified Mercalli intensity (MMI) or other scales. Traditional MMI values (MMI_T) for historical events can be analyzed using intensity-prediction equations developed

from MMI_T values estimated for instrumentally recorded events. The U.S. Geological Survey 'Did You Feel It?' (DYFI) system now collects and systematically interprets thousands of first-hand reports from felt earthquakes, using an algorithm to estimate Community Decimal Intensity (CDI) values within ZIP codes or geocoded cells. A comparison of the intensity-prediction equations developed independently for MMI_T and CDI data reveals a discordance in amplitude and distance-decay, with MMIT distributions suggesting more dramatic effects at greater distances, even when intensities are assigned according to more modern conservative practices. Using spatially rich CDI data for the 2011 Mineral, Virginia, earthquake, I show that CDI values within large cities are normally distributed; by design the DYFI system assigns mean values from multiple responses. I present evidence that MMI_T values tend to be controlled by extreme effects due to a fundamental tendency to report dramatic rather than representative effects. I introduce an empirical correction-factor approach to correct for this bias. This allows the growing wealth of well-calibrated DYFI data to be used as calibration in the analysis of historical earthquakes. As a case study I analyze the 1868 Hayward, California, earthquake, for which a particularly rich MMIT dataset is available, and estimate a magnitude of 6.4–6.6, a lower value than estimated by previous studies. I discuss the implications for probabilistic seismic hazard assessment of partially creeping faults.

Reconciling Intensity Prediction Equations with Ground Motion Prediction Equations

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Equations that predict intensity as a function of magnitude and distance are a useful tool for quantitative shaking hazard and loss assessment, and in the interpretation of both contemporary and historical earthquakes. The intensity prediction equations (IPEs) of Atkinson and Wald (2007) (AW07) have been very successful in describing the level and intensity of motions reported under the 'Did You Feel It?' (DYFI) program. Examination of the performance of AW07 for North American earthquakes, evaluated using an extensive compiled database of DYFI observations, suggests that there is little statistical basis for revising these equations. However, a problem with the AW07 equations is that they scale too uniformly (i.e. no magnitude or distance saturation effects) and thus predict unrealistically-large median intensities for large events (M>6) at close distances. Intensity data are insufficient to redress this issue, as they are too sparse in the magnitude-distance range of concern. The AW07 equations can be improved by 'closing the loop' between IPEs and ground-motion prediction equations (GMPEs) to reveal more suitable intensity scaling at large magnitudes and close distances. It has been shown (AW07) that DYFI intensity tracks instrumental measures of ground motion such as peak ground velocity very closely; moreover, statistical studies (Worden et al., 2012; W12) have provided robust correlations that relate DYFI intensity to ground-motion measures and vice versa. We use the equations of W12 to compare GMPEs (in particular Boore, Stewart, Seyhan and Atkinson, 2014) to AW07's IPEs. Recent GMPEs are constrained over a wide range of magnitudes and distances, enabling a more robust calibration of MMI predicted by the GMPE (via W12) to DYFI observations, over a broad overlapping data range (M3.5 to M6.5 are plentiful to 100km in both datasets). Based on this reconciliation of intensity and ground-motion predictions, we propose a revised version of our IPEs.

Quantitative Analyses of Did You Feel It? Data

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The availability of the 'Did You Feel It?' (DYFI) system for most felt earthquakes in the United States for the past fifteen years has provided an enormous database of millions of macroseismic intensity observations. DYFI data are also available for many global earthquakes, though most were made at a coarser resolution (until last year, when self-geocoding was implemented internationally). DYFI was designed to be consistent with traditional Modified Mercalli Intensity observations, and studies have generally shown this to be the case. DYFI data then, combined with traditional MMI observations, and coupled with near-coincident records from seismographic instruments, have provided a rich dataset suitable for quantitative analysis. Here we review our work with ground-motion/intensity conversion equations (GMICE) for California, and discuss their apparent regional variations when applied to global earthquakes, most demonstrably in Greece and Italy. These regional differences lead to the development of a GMICE for global earthquakes that includes terms for regional differences that may be applied in areas where the behavior appears similar to one of the well-constrained regions (California, Greece, and Italy). The high density of DYFI observations also makes the data suitable for a number of other quantitative analyses. We present preliminary results regarding DYFI intensity's well-behaved intraevent spatial correlation, its surprisingly small variance, and its response to soil amplification.

Performance of Several Low-Cost Accelerometers

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Several groups are creating low-cost host-operated accelerograph systems to support seismologists and engineers. These networks use very inexpensive sensors, host installation, computing, and telemetry to make networks economical to purchase and operate. The Advanced National Seismic System (ANSS) is exploring the potential of such systems for its networks.

Examples of such networks include the Community Seismic Network (csn.caltech.edu) and the Quake-Catcher Network (Cochran et al., 2009; qcn.stanford.edu). The overarching goals of such efforts are to increase spatial density of existing networks but at very low per-site cost. Host operation brings new people into citizen science fostering interest in the issues of earthquakes and adding measurement that can mitigate damage.

We summarize the performance of a wide range of low-cost sensors from testing at the Albuquerque Seismological Laboratory and elsewhere. They commonly have resolution from 12–16 bits over ±2 g, with a triaxial cost of about $100 to $200; they can have either USB or analog outputs; in our case USB outputs are recorded on software running on a laptop or within the instrument. We did 'box flip' tests for 0 Hz for sensitivity, offset, and axis orientations, and we measured amplitude transfer functions. These are some of the tests commonly applied to ANSS accelerometers of any given precision.

Two of the sensors we tested performed acceptably. Others, as tested, would not be viable in ANSS networks. The better devices have better resolution than the Kinemetrics SMA-1, which drove the early decades of earthquake building-code development. Axis orientation and sensitivity are less precise than in other ANSS accelerometers and might need to be corrected if applied for sensitive purposes (legal proceedings, design events, ground-motion models). However, in applications like ShakeMap where predictive uncertainties are nearly a factor of two, these low-cost devices are sufficient without correction.

Twitter Based Earthquake Detection and Characterization: System Assessment and Future Directions

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The U.S. Geological Survey (USGS) operates a realtime system that detects earthquakes using only data from Twitter—a service for sending and reading public text-based messages of up to 140 characters. The detector algorithm scans for significant increases in tweets containing the word 'earthquake' in several languages and sends internal alerts with the detection time, representative tweet texts, and the location of the population center where most of the tweets originated. It has been running in real-time for over two years and finds, on average, two or three felt events per day with a false detection rate of 8%. The main benefit of the tweet-based detections is speed, with most detections occurring between 20 and 120 seconds after the earthquake origin time. This is considerably faster than seismic detections in poorly instrumented regions of the world. The detections have reasonable coverage of populated areas globally. The number of Twitter-based detections is small compared to the number of earthquakes detected seismically, and only a rough location and qualitative assessment of shaking can be determined based on Tweet data alone. However, the Twitter detections are generally caused by widely felt events that are of more immediate interest than those with no human impact. We will present a technical overview of the system and investigate the potential for rapid characterization of earthquake damage and effects using the 22 million 'earthquake' tweets that the system has so far amassed. We will also investigate the potential use of other social media sources such as Instagram and Flickr for rapid impact assessment.

Earthquake Physics and Interaction

Oral Session · Friday · 3:45 PM · 2 May · Room 7/8 Session

Temporal and Spatial Clustering of Intermediate-Depth Earthquakes: Evidence for a Cascading Effect

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Intermediate-depth earthquakes are often observed in dense concentrations of seismicity called nests. While these clusters occur globally, the most concentrated of this activity is observed in the Bucaramanga nest in northern Colombia. We detect events within the Bucaramanga nest using a regional seismic network. Each day, there are approximately 18 detectable events, many with similar waveforms, and some with reversed polarity waveforms. Cluster analysis strengthens the observation of the reverse polarity families. We use a pair-wise correlation matrix of all available stations, with a minimum of three observations, normalized for the total number of observations. An average-linkage algorithm, divides the events clearly into two distinct groups. We use another agglomerative hierarchical method (single-linkage) to investigate events within these established groups.

We relocate these events using double-differences to illuminate two distinct features within the nest. Each of the two earthquake families corresponds, roughly, to one of these roughly linear features. We examine the recurrence interval of these two groups with respect to their new locations and observe clustering of the groups in time and space—in some cases showing repeating events within a few 10s of meters each another. We also investigate the focal mechanism of the repeating events to assess if the rupture might occur along the same fault patch, suggesting a cascading effect, possibly associated with thermal shear runaway.

Time-Dependent Earthquake Forecasts on a Global Scale

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We develop and implement a new type of global earthquake forecast. Our forecast is a perturbation on a smoothed seismicity (Relative Intensity) spatial forecast combined with a temporal time-averaged ('Poisson') forecast. A variety of statistical and fault-system models have been discussed for use in computing forecast probabilities. An example is the Working Group on California Earthquake Probabilities, which has been using fault-based models to compute conditional probabilities in California since 1988. An example of a forecast is the Epidemic-Type Aftershock Sequence (ETAS), which is based on the Gutenberg-Richter (GR) magnitude-frequency law, the Omori aftershock law, and Poisson statistics. The method discussed in this talk is based on the observation that GR statistics characterize seismicity for all space and time. Small magnitude event counts (quake counts) are used as 'markers' for the approach of large events. More specifically, if the GR b-value = 1, then for every 1000 M>3 earthquakes, one expects 1 M>6 earthquake. So if ~1000 M>3 events have occurred in a spatial region since the last M>6 earthquake, another M>6 earthquake should be expected soon. Event count models have been called natural time models, since counts of small events represent a physical or natural time scale characterizing the system dynamics. In previous research, we used conditional Weibull statistics to convert event counts into a temporal probability for a given fixed region. In the present paper, we move belyond a fixed region, and develop a method to compute these Natural Time Weibull (NTW) forecasts on a global scale, using an internally consistent method, in regions of arbitrary shape and size. We develop and implement these methods on a modern web-service computing platform, which can be found at www.openhazards.com and www.quakesim.org. We also discuss constraints on the User Interface (UI) that follow from practical considerations of site usability.

Seismic Evidence for Thermal Shear Runaway during Intermediate-Depth Earthquake Rupture

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Intermediate-depth earthquakes occur at depths where temperatures and pressures exceed those at which brittle failure is expected. There are two leading candidates for the physical mechanism behind these earthquakes: dehydration embrittlement and self-localizing thermal shear runaway.

We use seismic data recorded on a regional network around the Bucaramanga Nest, the highest concentration of intermediate-depth earthquakes in the world, to better constrain which mechanism is relevant during rupture.

The combination of high stress drop and low radiation efficiency that we observe for Mw 4–5 earthquakes implies a temperature increase of 600–1000° C for a centimeter-scale layer during earthquake failure. This suggests that substantial shear heating, and possibly partial melting, occurs during intermediate-depth earthquake failure.

Temporal and spatial clustering of these earthquakes shows aftershock sequences of repeating earthquakes, located within meters of each other and with similar focal mechanisms, in some cases within a few seconds of each other. This suggests that the same patch is rupturing over a short time interval, suggesting that the slow dissipation of the heat generated during previous rupture, allows for repeating slip along the same fault plane.

Our observations support thermal shear runaway as the mechanism for intermediate-depth earthquakes, which would help explain differences in their behavior compared to shallow earthquakes.

A Global Comparison of Crustal Earthquake Scaling from Stable Event Ratio Levels

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A challenge with using corner frequency to interpret stress parameter scaling is that stress drop and apparent stress are related to the cube of the corner frequency. In practice this leads to high levels of uncertainty in measured stress since the uncertainty in measuring the corner frequency is cubed to determine uncertainty in the stress parameters. We develop a new approach using the low and high frequency levels of spectral ratios taken between two closely located events recorded at the same stations. This approach has a number of advantages over more traditional corner frequency fitting, either in spectral ratios or individual spectra. First, if the bandwidth of the spectral ratio is sufficient, the levels can be measured at many individual frequency points and averaged, reducing the measurement error. Second the apparent stress (and stress drop) is related to the high frequency level to the 3/2 power so the measurement uncertainty is not as amplified as when using the corner frequency. Finally, if the bandwidth is sufficiently broad to determine both the spectral ratio low and high frequency levels, the apparent stress (or stress drop) ratio can be determined without the need to use any other measurements (e.g., moment, fault area), which of course have their own measurement uncertainties. For this study, we processed a wide variety of moderate-to-large crustal earthquake sequences using stable, high-resolution coda measurements and find overwhelming evidence that self-similar scaling is not supported by the data, regardless of the source model.

Stress Drop Studies of Earthquakes in the Southern North Island and Cook Strait Region of New Zealand

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We are using the empirical Green's function technique to estimate stress drops of events in the southern North Island of New Zealand and Cook Strait. In this region the Pacific Plate subducts obliquely beneath the Australian Plate along the Hikurangi Trough. The plate interface is strongly coupled, with slow slip events occurring downdip of the strongly coupled zone. The goal of our study is to determine if earthquakes occurring at the edges of the strongly coupled zone have higher stress drops than those located in parts of the study area. Our preliminary efforts are focused on the 2004–2005 Upper Hutt sequence (M3 to M5.6) occurring within the Pacific Plate downdip of the locked zone and events of the 2013 Cook Strait sequence (2 magnitude ~ 6.5 events). The results of this study will provide insight into stress loading along the interface and is part of a larger study to determine if stress drops of New Zealand earthquakes vary with tectonic setting.

75 Years of Frequency-Size-Distribution of Earthquakes: Observations, Models and Understanding

Poster Session · Friday · 2 May · Cook/Arteaga

A Lower Bound for Gutenberg-Richter's *b*-Value and Speculations on Fractal Dimensions

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The Gutenberg-Richter distribution corresponds to an exponential probability density function for magnitudes, which for moment magnitudes M_W is valid only

for $b>2/3$. Smaller b values are thus indicative of either sampling errors or of the use of magnitudes which do not scale as M_W.

In 1981, K. Aki speculated that the fractal dimension of the areas of the seismic ruptures should be related to b as $D=2b$; the supposition that seismic moments are fractally distributed implies that their fractal dimension should be $D=1.5b$ (so that for seismic moments $D>1$). This result validates Aki's speculation for the case where the average slip on a fault scales as the cubic root of the rupture area.

Using b-values and Apparent Stress to Characterize Stability of Hydraulic Fracture Growth

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Target formations of hydraulic fracturing are frequently sandwiched between layers with very different rock properties that tend to impede the progress of these fractures out of the target zone. Seismicity associated with the fracturing responds both to these differences in rock properties and potentially reflects the conditions necessary to breach these barriers. For example, when a fracture barrier is encountered, the energy required to break the rock increases relative to the overall size or moment of the event, making apparent stress an ideal candidate for tracking the behaviour of these fractures. Areas of low apparent stress are indicative of a more complex fracture pattern and show where the reservoir fracturing is most vigorous.

Furthermore, the b-value will add further insight into the characterizing the stable growth of these fractures: where the b-value is close to 1, the seismicity is consistent with fracturing along a fault in a stress-driven process. However, much higher b-values can be observed in hydraulic fracturing (up to and above 2) which invokes fluid-driven processes when smaller fractures are activated. The b-value information in combination with the stress information from the source parameters enable full characterization of the barrier failure processes by distinguishing cases where stress activated faults are breaching the barriers versus the progression of fracturing.

In our study b-values and apparent stress, together with individual failure mechanisms, were estimated in depth bins in three formations. Comparison these data in each layer resulted in the characterization of the failure processes in different depth bins and identifying the conditions under which fracture barriers were likely breached, and how these conditions are manifest in the observed mechanisms.

Microseismicty and Glacier Dynamics at the Vaughn Lewis Icefall, Alaska

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Microseismicity arising from within glaciers may illuminate both ice dynamics and mass balance. Ice falls in temperate environments are rapidly deforming glacial systems and constitute a unique environment to study glacier seismicity. We present a microseismic dataset that was collected in July 2012 at the Vaughn Lewis Ice Fall within the Juneau Icefield, Alaska. This dataset is accompanied by concurrent meteorological data and time lapse imagery.

We create a catalog of 1585 events that occur over a nine day period. We create a catalog from our continuous dataset using a basic short term average to long term average ratio method. All events are observed on at least three seismic stations. Most events are characterized by a spectral peak near $\sim$10 Hz and have a relatively narrow band width of about 5 Hz. Taking the maximum spectral displacement amplitude to be a proxy for magnitude, we find a Gutenberg-Richter power law relationship for our catalog with b=2.6.

We relate rates of seismicity to surface air temperature and find a correlation coefficient of 0.5. Time lapse imagery captures a strong diurnal variation in glacier surface velocities. During times of above and below freezing temperatures, the seismicity rate is 3.5 and 8.5 events per hour, respectively. Together, these observations suggest that melting may play a role in the generation of seismic events.

Evolution of the 2008 Mogul Earthquake Swarm, Reno, Nevada: Identifying Complex Structures in a Shallow Urban Seismic Sequence

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Increased sensitivity of seismic networks in northern Nevada highlights low-magnitude swarm behavior common in the Reno-Tahoe-Carson City area, with many sequences including felt events and with b-values <1. Over a five-month period beginning 28 February 2008, an unusually shallow sequence produced 38 $M_L \geq 3.0$ earthquakes in the Mogul-Somersett neighborhood of Reno, Nevada. The 26 April 2008 M_w 5.0 mainshock was preceded by 18 of 38 $M_L \geq 3.0$ earthquakes in two distinct foreshock phases that occur on closely spaced parallel structures. The second foreshock phase is characterized by increased activity with four $M_L \geq 3.0$ events on 15 April 2008 approximately 1 km NE of the first structure. The second phase also included two $M_L \geq 4.0$ foreshocks on 24 April 2008 and seven additional $M_L \geq 3.0$ foreshocks prior to the 'mainshock.' We relocate 1612 earthquakes occurring over 180 days with magnitudes greater than zero and a minimum of 20 defining phases using the double-difference algorithm of Waldhauser and Ellsworth (2000). The initial relocations indicate a complex fault zone with at least one auxiliary plane. We subsequently bin events using variable time windows and relocated each set independently to test if locating the entire swarm might be masking the temporal and structural resolution of the sequence. This relocation reveals several additional parallel and conjugate structures that have not been previously isolated. We use an empirical Green's function method to estimate source dimension and stress drop for the larger earthquakes to isolate stress variations within the active structures that may correlate with the evolution of the stress field inverted from moment tensor and short-period focal mechanisms. The complexity and shallow nature of the sequence suggests potential involvement of fluids and provides an image of numerous localized faults that may be an overall characteristic of urban Reno area seismicity.

How Complete is the ISC-GEM Global Earthquake Catalog?

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In January, 2013, the International Seismological Centre (ISC), in collaboration with the Global Earthquake Model (GEM) effort, released a new global earthquake catalog, covering the time period from 1900 through the end of 2009. In order to use this catalog for global earthquake studies, I determined the magnitude of completeness (Mc) as a function of time. First, I divided the shallow (focal depth $<$60 km) events into 7 time periods based on major changes in catalog processing and data availability. For each time period, I used 4 objective methods to determine Mc, with uncertainties determined by non-parametric bootstrapping. Due to differences between the 4 methods, the final Mc was determined subjectively by examining the features that each method focused on in both the cumulative and binned magnitude frequency distributions (MFD). The high end of the bootstrap confidence range was preferred so that there is 95% confidence that Mc is not underestimated. Spatial subsets were explored but did not improve the results. The time periods and Mc values are: 1900–1917, Mc=7.7; 1918–1939, Mc=6.9; 1940–1954, Mc=6.8; 1955–1963, Mc=6.5; 1964–1975, Mc=6.0; 1976–2003, Mc=5.8; and 2004–2009, Mc=5.7. Deeper events since 1964 yield Mc=5.7. Using these Mc values for the longest time periods they are valid for (e.g. 1918–2009, 1940–2009,. . .) the shallow data fits a Gutenberg-Richter relationship with b=1.05 and a=8.3, within 1 standard deviation, with no declustering. The exception is for time periods that include 1900–1917 in which there are only 28 events with M=Mc and the largest event is only 8.4. These few data do reject b=1.0 with 99% confidence and imply that b=1.9$\pm$0.3. Including poorly located events from the appendix catalog did not resolve this difference. Global studies should use the time period from 1918 onwards and the Mc values presented here. Before 1918 the magnitudes rely heavily on individual studies and might be improved by a consistent methodology.

Confidence Intervals for the Magnitude of the Largest Aftershock

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Aftershock sequences that follow large earthquakes last hundreds of days and are characterized by well-defined frequency-magnitude and temporal distributions. The largest aftershocks in a sequence constitute significant hazard and can inflict additional damage to infrastructure that is already affected by the main shock. Therefore, the estimation of the possible magnitude of the largest aftershock in a sequence is of high importance. Several decades ago Bath observed that on average the magnitude of the largest aftershock is approximately 1.2 units less than the magnitude of the main shock, which became known as Bath's law. However, this empirical law only gives an average value of the difference and does not specify the related statistical variability. Recently, more progress has been achieved in the statistical analysis of aftershock sequences. In this work, we compute the point estimator and confidence intervals for the magnitude of the largest aftershock in a sequence assuming that the aftershocks follow a well-defined frequency-magnitude distribution. Particularly we assume that the frequency-magnitude statistics can be described by the truncated Gutenberg-Richter law where the aftershock magnitudes are bounded from above by the magnitude of the main shock. We apply this analysis to several well-known aftershock sequences world-wide to construct retrospectively the confidence intervals for the magnitude of the largest aftershock in the sequences at a given confidence level. In addition, we consider a problem of estimating the magnitude and the confidence intervals of the largest aftershock in the prospective analysis of aftershock sequences. We use the information in the early times after

the main shock to constrain the magnitude of the largest aftershock to occur in the future. For this purpose, we employ the best point estimator for the largest aftershock computed from the analysis of the frequency-magnitude statistics of aftershocks.

Statistical Properties of Aftershock Sequences Generated by Large Subduction Earthquakes

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Large mega-thrust subduction earthquakes generate prolific aftershock sequences which last over an extended period of time and affect wide spatial areas. Among those aftershocks the largest ones can cause additional damage and pose significant risks to population and infrastructure. Therefore, modeling aftershock sequences of large subduction earthquakes is of considerable importance for seismic hazard assessment and earthquake risk mitigation. It can also play a prominent role in the ground shaking modeling of major mainshock-aftershock sequences. In this work, we analyze statistical properties of aftershock sequences of large subduction earthquakes world-wide which occurred from 1973 to present, including recent catastrophic events in Sumatra, Chile, and Japan. We use information provided in the NEIC catalog to extract 70 aftershock sequences generated by mainshocks of M7.0 and above. We construct their temporal decay rates and magnitude-frequency statistics. To model their temporal behavior, we estimate the parameters of the modified Omori law. In the magnitude domain, we model the frequency-magnitude statistics using the Gutenberg-Richter scaling relationship. We also analyze statistically the difference between the magnitude of the mainshock and the corresponding largest aftershock in the sequence and discuss this in terms of Båth's law. One of the main goals of this work is to investigate the variation in parameter values of the above empirical laws with respect to the magnitude of the mainshock. Our main finding indicates that most parameters do not depend on the magnitude of the mainshock. However, they show some variation in values across different subduction settings.

The Temporal Stability of b-Value estimates and its Implications for Regional and Local Studies

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The b value of the Gutenberg-Richter relationship is at the center of most seismic risk estimates, and has demonstrated its value in research focusing on seismicity or stress conditions. The estimate of this value depends on several factors, among which we can mention the homogeneity of magnitudes, the correct quantification of the minimum magnitude of completeness, the accuracy of the locations (especially in the case of local studies), the rate of seismicity, the installation and density of monitoring stations, etc.. However, a factor that has not been taken into account with the importance it deserves is the temporal stability of the estimation of b-values. A common procedure to obtain a b-value estimate is by compiling all available seismicity which is deemed suitable for an area of interest and calculate an estimate normalized per unit time. Clearly, if there are no anomalous siesmicity outbursts, as we progress in time, the b-value should remain stable even if we add more data.

One way to check for stability of the b-value estimates, is by updating the seismic catalog and comparing recent estimates with previous ones. Stability can also be assessed by performing estimates as as function of increasing the data recorded every year or time unit of interest, since the beginning of the recording period up to the current time. The problem with this way of working is that the oldest data, which often suffer from poor precision and errors, continue to be incorporated into each estimate affecting the results. In this work we present cases at regional and local level, where such procedure has affected the results of the estimates. We also show results of a simple alternative procedure that consists of making the estimates with respect to the increase of data in reverse order, i.e., starting with modern data and going backwards in time until a stable level is attained. Results are discussed and compared for regional catalogs of Italy, New Zealand and Mexico.

1/f and the Earthquake Problem: A Forecasting Framework Based on Fault Weakening and Scaling Constrained ETAS

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The difficulty of forecasting earthquakes can fundamentally be attributed to the self-similar, or "1/f", nature of seismic sequences. Specifically, the rate of occurrence of earthquakes is inversely proportional to their magnitude m, or more accurately to their scalar moment M. With respect to this "1/f problem," it can be argued that catalog selection (or equivalently, determining catalog constraints) constitutes the most significant challenge to seismicity based earthquake forecasting. Here, we address and introduce a potential solution to this most daunting problem. We introduce a framework to constrain, or partition, an earthquake catalog (a study region) in order to resolve local seismicity. In particular, we combine Gutenberg-Richter (GR), rupture length, and Omori scaling with various empirical measurements to relate the size (spatial and temporal extents) of a study area (or bins within a study area) to the local earthquake magnitude potential – the magnitudes of earthquakes the region is expected to experience. Within each sub-catalog, or bin, we apply a metric based on record-breaking interval statistics to detect accelerating seismicity indicative of local fault weakening. From this, we introduce a new type of time dependent hazard map for which the tuning parameter space is nearly fully constrained. We interpret 'hot spots' on this hazard map as ETAS source events (earthquakes) and calculate their potential hazard contribution (earthquake probability fields) from a self-similar ETAS model.

A Decade of Great Subduction Earthquakes – What Have We Learned From Their Ground-Motions?

Poster Session · Friday · 2 May · Cook/Arteaga

Source Scaling Relations of Subduction Earthquakes for Strong Ground Motion and Tsunami Prediction

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At present, there is a wide range of uncertainty in the median rupture areas predicted for a given seismic moment M0 (Nm) by current relationships for subduction earthquakes. Our goal is to develop an updated set of earthquake source scaling relations that will reduce the large degree of epistemic uncertainty and improve the accuracy of seismic hazard analysis and the prediction of the strong motion characteristics and tsunamis of future subduction earthquakes. We compiled a database of interface earthquakes that occurred in the major subduction zones with Mw ranging from 6.75 to 9.1. We chose to fit the data using self-similar relationships between rupture area S (km2) and M0 and between the average slip D (m) and M0. The regression analysis was found to support the self-similarity of scaling relations up to Mw 8.6, as also suggested by previous studies (Murotani et al., 2013; 2008, Somerville et al., 2002). Above Mw 8.6, the rupture area increases more gradually with Mw and the average displacement increases more rapidly with Mw. We attribute this to the saturation of rupture width. For both S and D, the mean values computed in this study are within one standard deviation of those reported in Murotani et al. (2008; 2013). Comparison of the present study results with those of Somerville et al. (2002) indicates smaller areas and larger slip for the same M0 in the new relationships. These differences are less prominent for the average slip, where results lie within one standard deviation. The standard deviation is considerably smaller than the values estimated in previous studies as a result of the larger number of records used in the regressions. Another factor that might have contributed to smaller standard deviations is that we did not use multiple models of the same earthquake in the regression analyses. Instead, we used judgment to select the most representative one based on various criteria such as the number and type of data used in deriving the model.

Ground-Motion Prediction Equations of Intermediate-Depth Earthquakes in the Hellenic Arc, Southern Aegean Subduction Area

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We compiled a response-spectra database from seismic records from subduction, inslab earthquakes with moment magnitudes of M 4.5–6.7 that occurred in the South Aegean subduction zone. We used the dataset to derive an updated set of ground motion prediction equations, which take into account the highly complex propagation of seismic waves in the Greek subduction zone based on the hypocentral depth and the location of the event relative to the low-velocity/low-Q mantle wedge. The analysis showed that ground motions from earthquakes with larger hypocentral depths (h>100 km), are amplified for along-arc stations (channeled waves effect) and are strongly attenuated in the back-arc region, due to the low-Q mantle wedge.

For shallower events (60 km<h<100 km), the corresponding differentiation of seismic motion for along-arc and back-arc stations is observed beyond a specific critical distance range, for which a qualitative model is presented. Moreover, for longer periods, both along-arc amplification and back-arc anelastic-attenuation factors strongly diminish, suggesting that the longer wavelengths of seismic waves are not affected by the complex geophysical structure, resulting in more similar ground motions for both back-arc and along-arc stations. Results for interface events (h<45 km) occurring along the outer Hellenic arc suggest their wave propagation is not affected by the presence of the low-velocity/low-Qs mantle wedge, but is mainly controlled by the differences of the anelastic attenuation between the Mediterranean and Aegean lithospheres. The usefulness of the employed model is demonstrated by the generation of synthetic strong-motion maps for various historical intermediate-depth events, for which macroseismic information is available. We were able to reconstruct the highly variable spatial pattern of damage distribution, especially for the deeper events (h>100km), which exhibit maximum macroseismic intensities along the outer Southern Aegean sedimentary arc.

Global Analysis of Rupture Duration for Intermediate and Deep Earthquakes

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We present a new dataset of more than 800 source time functions for intermediate and deep earthquakes (>50km) with magnitude larger than 5.5, between 2005 and 2012. Stacking of all available broadband seismograms after alignment on the P wave pulses enhances the coherent P wave energy, while reducing coda energy due to scattering. We use the stacked waveform to identify the beginning and the end of rupture history and reliably determine scaled duration. We finally obtain 610 source time functions globally distributed that not only allows depth-dependent analysis, but also a spatial examination of rupture durations with temperature, age and rate of convergence of the associated subducted lithosphere.

We find that depth- and magnitude-dependence of scaled duration varies from one subduction zone to another, suggesting a relation between earthquake depth, the characteristics of the subducting plate (temperature, rate of convergence, age), and the physics of rupture. Although significant scatter is present and trade-off between stress drops, rupture velocity and fault geometry may still need to be accounted for, our consistent methodology over the entire global data set is ideal for comparing rupture physics between different subduction zones and to study depth-dependence along a single subduction zone.

Seismic High-frequency Radiation During the March 20th 2012 (Mw 7.5) Mexican Earthquake, Using Strong Motion Data

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The shallow, trust earthquake was located at about 5 km offshore the limits of Oaxaca and Guerrero states near to Ometepec city and nucleated at a depth of about 20 km. There are several acceleration recordings from stations located near the epicenter, some of them recorded accelerations larger than 500 gal. The mainshock was followed by an exceptionally large number of aftershocks (more than 450 events during the first 30 hours and more than 1200 during the next four days). In order to study the high-frequency radiation distribution we use an aftershock as empirical Green function to generate the simulated acceleration record of the mainshock. Then the envelope of the simulated acceleration record is compared with the envelope of the observed acceleration record. Several distributions of perturbation times and radiation factors are proposed in order to improve the fitness. This procedure is carried out for all the components and stations simultaneously. The fitness of each trial is evaluated in terms of the residual value between the simulated and observed envelopes. This procedure is optimized following a genetic algorithms scheme. Resolution and sensibility of the high frequency radiation distribution are also discussed.

Advances in Understanding Earthquake Hazard in Central and Eastern North America

Poster Session · Friday · 2 May · Cook/Arteaga

Ground Motion Site-Effects from Multi-Method Shear-Wave Velocity Characterization at Portable Seismograph Stations Deployed for Aftershocks of the August 2011 Mineral, Virginia Earthquake

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We characterize shear-wave velocity-versus-depth (Vs profile) at 16 portable seismograph sites throughout the epicentral region of the 2011 Mw5.8 Mineral earthquake to investigate ground motion site effects in the area. We use a multi-method acquisition and analysis approach, where active-source horizontal shear (SH)-wave reflection/refraction as well as active-source multichannel analysis of surface waves (MASW) and passive-source refraction microtremor (ReMi) Rayleigh wave dispersion are interpreted separately. The time-averaged shear-wave velocity to a depth of 30 m (Vs30), interpreted bedrock depth and site resonant frequency are determined from the best-fit Vs profile of each method at each location for analysis. Using the median Vs30 value, which range from 270 m/s to 560 m/s, as representative of a given site we estimate that all 16 sites are NEHRP site class C or D. Further, based on the comparison of mapped surface geology to median Vs30 at our site locations, we do not see compelling evidence for using surface geologic units as a proxy for Vs30 in the epicentral region. We compare resonant frequencies calculated from ambient noise horizontal-to-vertical spectral ratios (HVSR) at available sites to predicted site frequencies (generally between 1.9 Hz and 7.6 Hz) derived from the median bedrock depth and average Vs to bedrock. Robust linear regression of HVSR to both site frequency and Vs30 demonstrate moderate correlation to each, and thus both appear to be generally representative of site response in this region. Based on Kendall Tau rank correlation testing, we find that Vs30 and the site frequency calculated from average Vs to median interpreted bedrock depth can both be considered reliable predictors of weak motion site response in the epicentral region.

Airborne Geophysical Survey Data used to Infer Geological Features Associated with Fault Slip in the Central Virginia Seismic Zone

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The location of active faults on which recent slip has occurred remains a challenge in intraplate seismic zones. In the Central Virginia seismic zone there are numerous ancient faults mapped at the surface and historical seismicity is diffuse (unlike the New Madrid seismic zone), suggesting alternative mechanisms for strain localization. We ask if certain geologic features are commonly associated with fault slip and likely to generate larger earthquakes such as the 2011 Mw5.8 earthquake. Airborne gravity, magnetic, radiometric and LiDAR surveys were flown over the Mw5.8 epicentral area in order to image surface and subsurface structures. Aftershock monitoring and surface observations indicate that the causative fault is buried, with aftershocks occurring mostly at 3–8 km depths along a SE-dipping zone. Smaller clusters of shallow (<4 km depth) aftershocks were also observed up to 15 km from the epicenter.

Gravity, magnetic, and radiometric data show a major bend in NE-trending anomalies close to the Mw5.8 epicenter, where complex geologic contacts are mapped on the surface and magnetic data suggest deeper contacts. The epicenter is also located near a prominent NE-trending gravity gradient extending >20 km in either direction. Gravity models suggest a shallow (2–4 km depth) low-density body within the hanging wall of the main-shock fault plane, probably representing metasedimentary rocks. Some shallow aftershock clusters are located near intersections between pre-existing faults and Jurassic dikes. They also occurred near gravity gradients which are somewhat lower than that near the main shock. Radiometric data show linear K anomalies along LiDAR lineaments near the shallow aftershock clusters (one which was mapped as a fault), suggesting K concentration due to muscovite crystallization during previous fault slip. These associations suggest that variations in rock density and/or rheology may have modified local stresses in a manner encouraging localized seismicity.

Earthquake Swarms Associated with the Saratoga-McGregor Fault System near Albany, NY

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Swarms of small earthquakes took place about 25 km southwest and west of Albany, NY in 2007, 2009, 2010 and 2011, with the 2011 swarm starting about 1 day before the 2011 M5.8 Mineral, Virginia earthquake and continuing for about 110 hours after the Mineral event. Relative locations of each of these swarms reveal consistent spatial trends. The 2011 swarm consisted of 11 events ranging from M2.7 to M0.9.

The relative locations trend about 350 m in a NE-SW orientation. The 2010 swarm was comprised of 13 events from M2.7 to M0.4, and it trended about 800 m in approximately an ESE-WNW orientation. A swarm of 8 events from M2.8 to M1.6 in early 2009 trended about 400 m in an NE-SW orientation, whereas 4 events with M3.0 to M1.6 took place in late 2009 with about a 5 km trend in an NE-SW orientation. The 2007 swarm involved 4 events with M2.7 to 1.2 and a possible trend of about 200 m in an NE-SW orientation. Each of these swarms was located in a different place, spanning about 16 km in a NE-SW orientation. The events in these swarms occurred on strike of and within a few kilometers of the extrapolated trace of the NNE-striking Saratoga McGregor (S-M) fault. Outcrops near the epicenters of the 2011 swarm exhibit NNE-striking fracture intensification domains with minor offset in the Ordovician Schenectady Formation. The 2010 swarm is also located on a WNW-trending lineament and has internal WNW-trends, consistent with WNW-trending faults similar to those in the Mohawk Valley. Possible focal depths for each of these swarms range from 8 to 18.5 km. These depths make correlation with specific surface structures tenuous, although seismic reflection data and fault traces through the Precambrian of the Adirondack Dome suggest that the S-M fault might be nearly vertical well down into the Precambrian. This conclusion is supported by the focal mechanism of an M2.6 earthquake on August 25, 2013 near the S-M fault about 60 km north of Albany.

A New Set of Focal Mechanisms for the Eastern Tennessee Seismic Zone

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We present a new set of focal mechanisms for eastern Tennessee seismic zone (ETSZ) earthquakes of magnitude 2.5 and greater occurring after 1999. The ETSZ is the second largest seismic zone in the central and eastern US, but has not produced a damaging earthquake in historic time. Previous research suggests that the ETSZ may be comprised of faults longer than 100 km, and so capable of producing damaging earthquakes in the future. Focal mechanisms are consistent and indicate strike-slip motion on steeply dipping nodal planes. Nodal plane orientation falls into two groups. In one, nodal planes strike N/S and E/W and in the other, NE/SW and NW/SE. ETSZ earthquakes are attributed to reactivation of a Grenville-age shear zone located in basement rocks in a recent local earthquake tomography study. The shear zone is associated with a major magnetic anomaly, the New York-Alabama lineament, and could extend further NE than the ETSZ. Extension of the shear zone is suggested by the Nov 10, 2012 Mw 4.3 event in eastern Kentucky; the event focal depth is 13 km and the focal mechanism exhibits strike-slip motion on steeply dipping, NE striking nodal planes. The new set of ~50 focal mechanisms, with 10 of those being outside the ETSZ, will examine similarities in orientation and depths of events in and surrounding the ETSZ. New solutions will supplement a set of 26 previously calculated focal mechanisms and are expected to be consistent with these solutions. A statistical analysis will examine hypocenter and epicenter distributions as well as nodal plane orientations to determine any significant spatial similarities between events. The nodal planes of the focal mechanisms are expected to be oriented parallel to linear groupings of hypocenters. This would suggest the presence of large, through-going faults in the ETSZ. Consistent nodal plane orientation and depth of events would suggest that the ETSZ is produced by large faults, which may extend beyond the currently known region.

Hazard Associated with the Eastern Tennessee Seismic Zone

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Several observations suggest that the eastern Tennessee seismic zone (ETSZ) could pose a significant hazard to populated areas and critical facilities. One lesson learned from the Mw 5.8 Mineral VA earthquake is that seemingly harmless regions of concentrated but small magnitude earthquake activity can produce damaging earthquakes. There are several such regions in the eastern US but none as potentially hazardous as the 200 km long ETSZ. A seismotectonic model for the ETSZ derived in a recent local earthquake tomography study associates the ETSZ with an ancient plate boundary that accommodated primarily transform motion between Laurentia and Amazonia during the ~ 1 Ga Grenville orogeny. ETSZ earthquakes are attributed to the reactivation of strike-slip faults in the basement associated with this boundary. Several observations support this seismotectonic model including consistent focal mechanism solutions displaying strike-slip motion and alignment of hypocenters in near-vertical segments consistent with the apparent trends and steep dips indicated by the focal mechanisms. An idea of hazard potential can be obtained using the distribution of hypocenters. Within the most seismogenic portion of the ETSZ, hypocenters align in clusters extending roughly 50 km in length and extending between 5 and 20 km. Using a standard relationship between fault area and moment magnitude, we could expect a magnitude 7 earthquake to occur if the entire illuminated fault surface ruptures. This is undoubtedly an overestimate but points to the potential for ETSZ earthquakes to damage populated areas and critical facilities. The seismotectonic model will be discussed as well as statistical methods being using to better delineate active basement faults.

Discerning Faults Responsible for the Charleston, South Carolina Earthquake of 1886

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The 1886 Charleston, SC earthquake was the largest earthquake in the U.S. east of the Appalachian Mountains, with an estimated magnitude of 6.8 to 7.3. The earthquake serves as the design earthquake for many built structures in the region, but the causative fault(s) remain unknown. Reprocessed seismic reflection data reveal numerous faults cutting the Cretaceous and younger Atlantic Coastal Plain (ACP) strata in the epicentral area. The faults are identified on seismic profiles by vertical displacements of strata, abrupt but small changes in dip, and folding of the ACP strata. Short-wavelength filtered aeromagnetic data reveal a localized WNW-trend that suggests a variation in basement rock geometry beneath the ACP strata. Offsets or disruptions of these WNW-trending anomalies correspond to seismically imaged faults cutting ACP strata. One of these faults, previously termed Gants fault, shows ACP strata (or reflector) offsets or folding of ~50 m vertically. The vertical uplift is nearly equal through almost the entire ACP section with little or no thinning across the fault, indicating the motion is primarily post-Cretaceous in age. The fault lies almost directly beneath the town of Summerville, where ground deformation was focused during the 1886 earthquake. The Gants fault is evident on two seismic profiles and trends NE, which is nearly perpendicular to the magnetic anomalies. The fault coincides with a linear trend of disruption of the magnetic anomalies. Another NE-trending fault crossing beneath the Ashley River, ~15 km NW of Charleston, is defined by reflector terminations and a change in total magnetic field patterns. This fault coincides with the greatest deformation observed along three railroad lines after the earthquake, including lateral offset of the tracks and NE-trending surface fissures. The correspondences between ground deformation, seismically imaged faults, and magnetic lineations suggest that both faults moved during the 1886 earthquake.

Lg Propagation and Attenuation Across Continental Margins, Scotia Basin

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The Scotia Basin in easternmost Canada is a classic passive conjugate margin. The Basin is located on the northeastern flank of the Appalachian Orogen and covers an area of approximately 280,000 sq, km, half of which lies on the present-day continental shelf, and the other half on the continental slope which ends in oceanic crust. Because Lg wave propagating across a thin crust or a crust with drastic changes in the thickness loses energy quickly (Kennett, 1986), the transitional structures like Scotia Basin may cause high attenuation or blockage of Lg. The variation of Lg in regions with both continental and oceanic environments has been rarely investigated (Tae-Kyung Hong, 2010). MN, and mblg magnitude scales, which are used by the Canadian National Data Center for routine reporting of earthquakes, are based on the Lg phase. Thus, it is desired to have a realistic estimation of Lg attenuation for the area to correctly estimate magnitude of offshore events which are potential threats of tsunami and seismic hazard to onshore. In this study we investigate the Lg propagation and attenuation within the four regions on the continental margin of most eastern Canada, frequency-dependent QLg will be determined based on the inversion technique introduced by Benz et al. (1997) and McNamara et al. (1996) and the margin of the error for calculated Q will be determined by a resampling method. This study complements previous studies on estimating QLg values for eastern Canada by extending the region of interest into the southeastern most part of Canad. No study of QLg specifically for these regions is known. Data from 100 earthquakes recorded on the Canadian National Seismic Network, occurring during 2004 to 2013 within the crust (<30 km depth), have been collected for this study. The primarily results for Q values were calculated using 10 events for 5 one-octave frequency bands from 0.5 to 16 Hz primarily value of $Qo = 540$, $n = 0.48$ for frequency.

Initial ENA Empirical GMPEs Using the NGA-East Database

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We develop an initial set of empirical ground motion prediction equations (GMPEs) for eastern North America (ENA) using the new Next Generation Attenuation (NGA) East ground motion database. This study provides predictive relationships for a particular measure of horizontal ground motion as a function of earthquake magnitude and fault type, distance from source to site, and local soil condition. We

use the two-stage regression approach of Joyner and Boore (1993) and thus develop both within and between event sigma estimates. We also estimate single station sigma from stations with 30 or more recordings and obtain estimates for ENA of 0.3 as compared with total sigma estimates of 0.4–0.5 (natural logarithm). The resulting equations are for peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute-acceleration spectra (PSA) at periods between 0.02 sec and 2 sec. In our analysis we avoided records from the higher attenuating Gulf Coast region and used a total of 6544 records of PGA with a distance range from less than 10 km up to 3500 km. The available data for regression become less for longer periods. The developed empirical GMPEs, though not well constrained from large magnitude observations, fit the ground motions from small to moderate magnitude (M<6) earthquakes in ENA quite well based on residual analysis. The initial ENA empirical GMPEs will be improved in the near future by adding ground motion estimates from intensity observations for historical M6-7 earthquakes (see Cramer, 2013, this meeting).

Improving Stress Drop Measurements from EGF – Scaling and Stress Release in the Darfield-Christchurch, New Zealand Earthquake Sequence

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We are developing a direct wave, spectral ratio analysis approach that includes realistic estimates of uncertainties and has strict objective criteria for assessing the quality of an EGF (empirical Green's function) derived spectral ratio (Abercrombie, 2013). Comparing this approach to other methods reveals significant random and systematic biases, enabling us to improve our understanding of the real uncertainties. The Canterbury earthquake sequence that began with the M7.1 Darfield earthquake in 2010, and includes the devastating M6.2 Christchurch earthquake in 2011 is a very active sequence within a low strain rate tectonic setting. High quality recording and accurate relocations make this an ideal sequence to investigate any spatial, temporal, or magnitude dependence to stress drop. The largest earthquakes appear to have relatively high stress drops, consistent with the high ground accelerations and damage in Christchurch. This observation is also consistent with the hypothesis that faults in low-strain rate regions with long inter-event times rupture in higher stress drop earthquakes. The large number of earthquakes in the sequence enables us to apply the same approach to a wide range of magnitudes (M∼2–6) recorded at the same stations, and so minimize the effects of any systematic biases in results. There are also sufficient stations to investigate inter-station variability. We follow Abercrombie (2013) to calculate stress drop using direct P and S waves for groups of earthquakes (M>2) surrounding each of the M>5 events. In each subset we investigate whether stress drop shows any dependence on magnitude. The spatial migration of the sequence, from Darfield through Christchurch and then offshore enables us also to investigate whether we can resolve any spatial or temporal variation within stress drop. We compare our results to estimates made by other studies using different methods, and also to other regions studied using the same EGF method.

Citizen Seismology: Citizens Helping Science Helping Citizens

Poster Session · Friday · 2 May · Cook/Arteaga

Detecting Frequency Content of Ground Motion with Smart Phones using Wavelet Analysis

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Currently, advanced traditional seismic networks only have stations every 10 km cover a limited areas. Contribution of smart phones sensors have the potential to provide much higher resolution in urban areas for variety of purposes. Smart phones can provide intensity of an earthquake to emergency responders and may provide invaluable information to track frequency changes of structural vibration. This is challenging because low quality sensors in smart phones have high self-noise and low signal to noise ratio. In this study the ability of smart phones to identify the frequency content of complex ground motion is investigated. To do so, an artificial non-stationary synthetic signal series with a sum of various time varying frequency functions containing sine signals are applied to uni-directional shake table and response is recorded. Three sensors; a high, a low cost and those in smart phones are tested with the same ground motion instantaneously. Comparison of data are made between smart phones and a reference high quality Capacitive Force Micromachined (with 32-bit high resolution, and 120 dB dynamic range) strong motion sensor. The validity of using smartphones is determined with level of instrumental self-noise and frequency responses. Records from three sensors are used to investigate their frequency content in time domain with wavelet analysis which can detect abrupt frequency changes in a non-stationary signal. The frequency limits for which mobile phones are successful to distinguish, are reported and their potential to capture frequency content of ground motion is discussed in detail.

Limits of Smart Phones as Seismic Sensors

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There is a growing trend on the use of smart phone sensors in seismology and civil engineering. In recent years, many Apps made available to use acceleration of phone sensors from earthquake detection to structural health monitoring. Researchers use mobile phone apps to collect, share or process data for technical, scientific as well as educational purposes. Although challenges are substantial such as unknown goodness and robustness of data, smart phones have the potential to transform seismology particularly real-time seismology. In this study, three sensors; a high, a low cost and those in smart phones are employed to investigate the reliability of mobile phones to detect ground vibration. To do so sinusoidal forced vibration induced to a unidirectional shake table with frequency ranging from 0.1 to 4 Hz and with an amplitude ranging from 0.1 to 1 g. Data obtained from low-cost and smart phone sensors are compared with reference Capacitive Force Micromachined (with 32-bit high resolution, and 120 db dynamic range) strong motion sensors. Amplitudes obtained from both tested and reference sensors are subtracted to calculate amplitude residuals which are used to investigate frequency dependency. Furthermore, sensitivity and level of instrumental self-noise, effects of variability of sample per seconds of smart phones, resolution of records, frequency and phase responses are discussed. Hence this study concludes with information regarding to usability of smart phones to capture ground motion by addressing their frequency and amplitude boundaries along with recommendation for future Apps developments in seismic studies.

Relationship Between Seismic Intensities (MMI), PGA, and PGV for the April 20, 2013, Mw6.6 Lushan, China Earthquake and a Comparison with North America

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The April 20, 2013 Mw6.6 Lushan, China earthquake is significant because it typifies an upper-crustal, reverse-faulting event that could occur beneath many highly-populated cities in seismically active regions throughout the world. We report a field determination of the Modified Mercalli Intensity (MMI) within 35 km of the epicenter where the geologic site conditions are uniform (0–10 m soil overlying hard rock) and the predominant building type is reinforced concrete. MMI values vary from MMI IX to VI. Eight accelerometers within 40 km of the epicenter recorded peak ground acceleration (PGA) ranging from 1005–270 cm/s2 and peak ground velocity (PGV) ranging from 25.6–11.8 cm/s. There is a close quantitative correlation between MMI and both PGA and PGV. However, the MMI-PGA/PGV correlations for the Lushan earthquake show some significant differences with the empirical relations for MMI-PGA/PGV as determined for California and eastern North American. Significantly, for MMI VI to VII, the Lushan data show PGA values that are 2–3 times higher than is predicted for either California or eastern North America.

Developing Ground Motion Estimates from M>6.0 Earthquake Intensity Observations for Use in ENA Emperical GMPEs

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Instrumental ground motion observations for eastern North America (ENA) earthquakes are limited to M<6.0. Intensity observations for M>6.0 ENA earthquakes are available. I convert intensities to ground motion estimates for use as constraints in empirical ground motion prediction equation (GMPE) development. My intensity to ground motion conversion uses the relations of Dangkua and Cramer (2011) for ENA. For a given intensity level, the ground motion estimate is assigned to the mean log distance for that intensity and for a given earthquake. This methodology is validated using the 1988 M5.9 Saguenay, QC and 2011 M5.7 Mineral, VA earthquakes, which have both ground motion and intensity observations. Magnitudes of historical events are taken from Cramer and Boyd (2014) for M7 ENA earthquakes. Magnitudes of M6 historical earthquakes are confirmed using the mean intensity Monte Carlo approach of Cramer and Boyd

(2014) with the 1925 M6.2 Charlevoix, QC and 1988 M5.9 Saguenay, QC earthquakes as reference events. Mean magnitude estimates for the 1843 Marked Tree, AR and 1870 Charlevoix, QC earthquakes are M5.9–6.0 and M6.0–6.1, respectively. 95% confidence limits on the magnitude estimates are ±0.3–0.4. The 1870 earthquake magnitude estimate is consistent with Ebel (2013). The intensity data for the 1895 Charleston, MO earthquake is too contaminated by site effects (Bakun et al., 2003) to be useful at this time. For use in GMPE development, only the M7 1811–1812 New Madrid and 1886 Charleston, SC earthquakes plus the M6.2 1925 Charlevoix, QC earthquake provide useful additional constraints over a distance range of 50 to 1200 km. The 1929 M7.2 Grand Banks earthquake only provides constraints at large distances of 1200 to 1400 km due to the offshore location of the event. Other historical events are in the magnitude range of existing ground motion observations or the 1925 event, and hence not as useful.

Frequency Distribution of JMA Seismic Intensity and Ishimoto-Iida Law

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Through our own experiences, we are aware that large seismic shakings are rare events. Past records show that large intensities are less frequently observed than small intensities, and frequency distribution of observed intensities obeys an exponential law, which is known as the Ishimoto-Iida law [Ishimoto & Iida, 1939]. We investigate statistics of JMA Intensity data by means of the Ishimoto-Iida law. While it is always difficult to represent complex ground motion with one index, JMA Seismic Intensity has been widely accepted in the Japanese society and it is often utilized when seismologists communicate with the public and discuss hazard assessment and risk management. Following a long history of JMA Intensity based on human sensory, JMA Instrumental Intensity was introduced in 1996, and the number of seismic intensity observation sites has substantially increased and the spatial coverage has improved vastly, and as a result JMA Intensity is going to become a unique quantitative dataset for strong motions in Japan. The Ishimoto-Iida law explains the statistics of the observation well for the recent instrumental as well as for pre-instrumental intensity data, At approximately 100 stations with long recordings, exponents of the Ishimoto-Iida law are almost identical between pre-instrumental and instrumental intensities, and continuity of observations is confirmed from this particular point of view. The observed numbers of large intensity is slightly less than extrapolated and predicted from those of small intensity assuming the exponential relation. Large number of intensity observations are annually reported in Kanto area.

Earthquake Physics and Interaction

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The Seismic Quiescence Phenomenon in Taiwan

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To detect the anomaly of seismic activities of large earthquakes in Taiwan, we first analyzed earthquake catalogue to obtain the minimum magnitude, Mc=2.4, for completeness of the catalogue. This means that earthquakes with magnitudes greater than Mc are complete and then can be used for the computation of seismicity rate changes, which are represented by the Z-values (with positive and negative values representing, respectively, active and inactive seismicity). To study the precursory phenomena, we examined pre-seismic seismicity prior to 65 large inland and offshore earthquakes with M>6.0 occurred during 1990 to 2013. After eliminating the obvious interactions between events, the Z-values are calculated for 7 inland and 10 offshore mainshocks. From the complete earthquake catalogue, the aftershocks of two very large earthquakes can influence the Z-values of related main shocks. Hence, 8 main shocks are removed.

The variations of Z-values for 2 inland events show the appearance of anomalous states of seismic quiescence in 20 or more years prior to the events. Meanwhile, the length of time interval of seismic quiescence is positively related to the magnitude of the main shock. By contrast, precursory quiescence was absent or cannot be clearly recognized for offshore main shocks.

The Construction of the Fault Model in Ordos, China

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Based on the main active faults of Ordos and the relocation results of the earthquakes of China from 2003 to 2012, we built a fault model of Ordos and the surrounding areas which included the longitude and latitude of the fault ends, the dip angle and the locking depth of the faults. Furthermore, based on this fault model and the GPS data of this area from 1997 to 2007, we used the least squared method to calculate the slip rate of faults of Ordos by considering the influence of the independent dislocation of different faults on the GPS data and the constraints between the adjacent faults. Thus, we initially built up a dynamic model of the faults of Ordos. And, we compared the results of slip rate of some of the faults with those obtained by other research groups and made a summary.

Quantifying and Explaining the Frequency-Dependent Radiation Pattern of the 2000 Tottori, Japan, Earthquake

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Observed radiation patterns from earthquakes transition from a double-couple pattern at low frequencies to an isotropic one at high frequencies. This difference is generally attributed to scattering from small-scale heterogeneities in the uppermost crust. In addition, fault roughness can also lead to deviations from the double couple radiation due to variations in the local radiation pattern from different sections of the fault. We quantify the latter effect analytically. We derive an expression for the far-field radiation pattern that is the superposition of a double-couple term and a correction term, arising from deviations from planarity, that fills in nodes in the double-couple pattern. The correction is important only at high frequencies. Our objective is to determine the relative importance of scattering and fault nonplanarity on the high frequency radiation pattern. We do so by calculating RMS accelerations at different azimuths of the 2000 Mw 7.3 Tottori, Japan, event in different frequency bands. This event is ideal to study because of its virtually pure strike-slip nature and its tremendous station coverage provided by the K-NET and KiK-net strong ground motion stations in Japan. We observe the transition toward an isotropic radiation pattern at ~2 Hz. We are comparing these observations to predictions, both from our analytical results of nonplanar faults, and to simulations in 3D scattering media.

Applying the Time-Domain Moment Tensor Inversion Technique to Regional Earthquake Data in the Puerto Rico-Virgin Island Region

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Although the Caribbean plate region is characterized by slow (~2 cm/yr) plate motions, it is still prone to earthquakes and tsunamis along its boundaries where most of the land is concentrated. Moreover, most of the population residing on these active tectonic regions is concentrated along the coastal areas, thus resulting in an increasing seismic hazard in the eventuality of tsunamigenic earthquakes. Being able to detect and alert coastal populations in a timely manner is critical to safeguard lives and infrastructure. This research project explores a thoroughly validated, well-formulated time-domain moment tensor inversion code in order to obtain in quasi real-time faulting parameters of significant regional earthquakes in the Puerto Rico – Virgin Islands region. The inversion code has been developed by researchers at the Berkeley Seismological Laboratory, whose main attractive is to decrease the time it takes to have an estimate calculation of a moment tensor for any major earthquake using regional data, approximately less than 7 minutes of an earthquake's origin time. Three seismic events in the region have been used as testbed to the inversion code configured for this area. In order to compare our results, previously computed and published moment tensor inversions from the Global CMT and USGS for the same events were used to assess the deviations from results obtained in this study. Our results indicate the inversion method is capable of reproducing the regional and teleseismic solutions, and thus can be incorporated into daily earthquake location operations at the Puerto Rico Seismic Network (PRSN) for quick estimation of faulting mechanisms and tsunami warning purposes.

A Fluid-Induced Seasonally Modulated Earthquake Swarm near Maupin, Oregon

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From December 2006 to November 2011, the Pacific Northwest Seismic Network (PNSN) reported 467 earthquakes in a swarm 60 km east of Mt. Hood near the town of Maupin, Oregon. The swarm included 20 $M_D \geq 3.0$ events, which account for

over 80% of the cumulative seismic moment release of the sequence. Relocation of forty-five $M_D \geq 2.5$ earthquakes and moment tensor analysis of nine $3.3 \leq M_w \leq 3.9$ earthquakes reveals right-lateral strike-slip motion on a north-northwest trending, 70° west dipping, 1 km^2 active fault patch at about 17 km depth. The swarm started at the southern end of the patch and migrated to the northwest at an average rate of 1–2 m/d during the first 18 months. Event migration was interrupted briefly in late 2007 when the swarm encountered a 10° fault bend acting as geometrical barrier. The slow migration rate suggests a pore pressure diffusion process. We speculate that the swarm was triggered by flow into the fault zone from upwards-migrating, subduction-derived fluids. Superimposed on the swarm is seasonal modulation of seismicity, with highest rates in spring, which coincides with the maximum snow load in the nearby Cascade Mountains. The resulting surface load variation of about 4×10^{11} N per km arc length causes 1 cm annual vertical displacements at GPS sites in the Cascades and appears sufficient to modulate seismicity by varying normal stresses at the fault and fluid injection rates into the fault zone.

Fifty Years of Tsunami Science: from the 1964 Earthquake and Tsunami to the SAFRR Tsunami Scenario - Advances in Tsunami Source Characterization, Numerical Analysis and Hazard Mitigation

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California Marshes as Recorders of Paleotsunamis: Example from Pillar Point

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We report on the initial results of a statewide effort to search for geological evidence of past tsunamis impacting the California coast. Several historical distant-source tsunamis have inundated portions of the northern and central California coast, and recent numerical tsunami modeling studies identify a threat to California by distant-source tsunamis, especially from the eastern Aleutian Islands subduction zone. Surveys were conducted at 20 coastal marshes and included site visits, mapping, and coring of shallow surface sediments to determine if evidence for past tsunamis exists. Here, we focus on data collected at Pillar Point Marsh on the central California coast during four field efforts from October 2011 to March 2013. In all, 94 cores were collected and included 3-cm and 6-cm diameter gouge cores, 7.6-cm diameter vibracores, and 10.2 and 15.2-cm diameter push cores.

Clean sand deposits interbedded with marsh sediment were observed in most cores taken in the Pillar Point Marsh and an associated ephemeral lagoon/pond. We looked for typical features of tsunami deposits including deposit geometry (sheet-like, generally landward thinning), evidence of marine origin (sand similar to offshore or beach sands; presence of marine diatoms or foraminifera, marine geochemical indicators), grading (normal, suspension grading, landward fining), contacts (sharp erosive basal contact), and evidence of high speed flow (rip-up clasts, erosive contacts) followed by still water (mud lamina, organic debris cap). Microfossil assemblages, grain-size distributions, geochronology, and provenance of sand layers provided key information to assess if deposits were formed by tsunami. We interpret a widespread sand deposit near the surface of Pillar Point Marsh to be formed by the 1946 Aleutian Islands tsunami based on sedimentological characteristics, deposit geometry, and 137Cs dating. Evidence for the formative mechanisms for sand deposits below the upper sand is also presented.

Observations on the 1964 Distant-Source Tsunami Deposit at Crescent City, California

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As part of the U.S. Geological Survey Science Application for Risk Reduction (SAFRR) project, select low-lying sites on the northernmost California coast were evaluated for geological evidence of past inundation and deposition by distant-source tsunamis (DST). At Crescent City (41.7°N), evidence for inundation and deposition in 1964 by a DST, resulting from the M9.2 Alaska earthquake, includes verification from eyewitness accounts, post-event surveys, and geological coring efforts several decades after the event. For this study we used GPS-based field mapping and coring, along with grain-size, microfossil, and Pb-210/Cs-137 analyses to evaluate the 1964 deposits at three marsh sites, including a marsh north of Crescent City that had not been previously evaluated in detail. The primary goals of the study are twofold: (1) to describe and compare characteristics of the 1964 tsunami deposit with storm deposits (and, in some cases, with the AD 1700 Cascadia subduction zone earthquake tsunami deposit); and (2) to use the results of our data on the distributions and physical characteristics of the 1964 deposits to evaluate the potential for identifying prehistorical (pre-1800s) DST deposits in the coastal stratigraphic record for northern California. We used Cs-137 to verify the 1964 tsunami deposits at our study sites, which range from barely visible, < 3 mm thick sediment layers to > 4 cm thick accumulations of silt, very fine sand, and detritus. Marine diatoms are prominent in the 1964 deposits, to include a 1 cm thick silty deposit ~ 700 m inland, and a sand and detritus deposit adjacent to the coast in which the diatom data provide evidence for deposition by subsequent tsunami waves. To date we have not identified with certainty DST deposits in addition to the 1964 deposits in the stratigraphic interval above the AD 1700 tsunami deposit. Therefore, for instance, at Crescent City, there is as yet no evidence for inundation and deposition associated with a DST in 1788.

Geospatial Methods in Support of Tsunami Research

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Tsunami research and inundation mapping utilize a wide variety of data and geospatial analysis techniques. Imagery, digital elevation models (DEMs), LiDAR and other data can be integrated into a GIS and applied as input into tsunami models. We summarize some of these integration techniques and applications along with new sources of data and geoprocessing tools. High quality bathymetric and topographic data sets can be difficult to source and merge, but they are integral to tsunami modeling. Key to the discussion of data integration are the concepts of vertical datum transformations and edge matching between data sets. Also, a few ways GIS is being used to support tsunami research at the Alaska Earthquake Center (AEC) will be covered, from data acquisition to the processing of DEMs. And finally, as a portal for public consumption, AEC's Alaska Tsunami Online Mapping interface, leveraging Google Maps, will be highlighted as a way to bring the products of the research directly to the public and to those making community evacuation plans.

Tsunami Evacuation Modeling for Cannon Beach, Oregon

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Timely evacuation is the most effective way to protect people living in a tsunami inundation zone. For Oregon coastal communities facing local tsunamis from Cascadia Subduction earthquakes, evacuation time is short, so it is critical to define the best routes and to know where alternative measures may be needed. We adapted the anisotropic path distance method of Wood and Schmidtlein (2011, 2012) to make a new evacuation time model for the City of Cannon Beach, Oregon. The model uses land cover and slope maps to determine speed conservation values (SCV) which represent the proportion of maximum travel speed possible in different areas. We used high resolution lidar and orthophotos to prepare highly detailed and accurate SCV maps. When our initial models produced results that were at odds with local experience we developed a simple technique to visualize the paths chosen by the model which allowed us to identify areas where the paths did not make sense. We then modified the SCVs for various land cover types to arrive at realistic evacuation routes. The model allows us to easily test the impact of changes like bridge failure or co-seismic ground failure to evacuation time and routes. We also used the model to map evacuation efficiency, the ratio of modeled evacuation time to the time required to reach safety by a straight line path. This allows us to highlight areas where addition of pathways might reduce evacuation times. The path visualization

technique also allows us to estimate the proportion of total evacuation traffic that is likely to take a particular path. Results like these empower planners to choose the best routes and decide where to install way finding aids such as signage or emergency lighting. For display purposes, we labeled each building in the study area with its evacuation time, and included tsunami first-arrival contours based on the same simulation used to define the evacuation zone.

Seismic Monitoring Capabilities of the Caribbean and Adjacent Regions Tsunami Warning System

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Over 75 tsunamis have been documented in the Caribbean and Adjacent Regions during the past 500 years. Since 1500, at least 4484 people are reported to have perished in these killer waves. Hundreds of thousands are currently threatened along the Caribbean coastlines. In 2005 the Intergovernmental Coordination Group for the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE EWS) was established. It recommended the following minimum seismic performance standards for the detection and analysis of earthquakes: 1) Earthquake detection within 1 minute, 2) Minimum magnitude threshold = M4.5, and 3) Initial hypocenter error of <30 km. The implementation plan of the CARIBE EWS currently includes 115 seismic stations in the Caribbean and Adjacent Regions. The NOAA National Weather Service Caribbean Tsunami Warning Program prepares and distributes monthly reports on real time and archived seismic data availability of the contributing stations at the US Tsunami Warning Centers, the Puerto Rico Seismic Network and IRIS. As of early 2014, 99 of the proposed stations are being contributed by national, regional and international seismological institutions. Recent network additions (Nicaragua, Colombia, Mexico, Cayman Islands, and Venezuela) have reduced detection threshold, time and location error throughout much of the Caribbean region and Central America. Specifically, earthquakes (>M4.0) can be detected within 1 minute throughout much of the Caribbean. The remaining exceptions to this standard for detection are portions of northern South America and Mexico. Another performance criterion is 90% data availability. Currently 60–70% of the stations meet this standard. The presentation will further report on the status of the CARIBE EWS seismic capability for the timely and accurate detection and analysis of earthquakes for tsunami warning purposes for the Caribbean and Adjacent Regions.

Stochastic Models of Earthquake Slip for Probabilistic Tsunami Modeling

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Probabilistic Tsunami Hazard Assessment (PTHA) requires sampling the stochastic space of possible seismic events that may cause tsunamis. The pattern of slip on a given fault geometry can greatly affect the resulting inundation, particularly in the nearfield. However, variations in inundation are most sensitive to the slip distribution on the portion of the fault nearby, and relatively insensitive to the slip pattern on more distant portions of the fault. Moreover, the mapping from slip on the fault plane to seafloor deformation is a smoothing transformation, so that higher wavenumber modes may be less important, particularly on deeper faults. This suggests that considerable dimension reduction should be possible when exploring the high dimensional stochastic space. Ongoing work will be presented on exploration of these ideas, conducted in relation to a PTHA study of Crescent City, California and a potential subduction megathrust event on the Cascadia Subduction Zone.

A Coupled Model for Dynamic Wedge Failure, Coseismic Landslides, and Tsunami Propagation for Shallow Subduction Earthquakes

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In Ma and Hirakawa (2013), we proposed that coseismic submarine landslides can occur because large seafloor uplift due to extensive wedge failure significantly steepens the upper wedge slope. For a wedge on the verge of failure initially any steepening of slope can easily lead to landslides, which is an alternative explanation for the large horizontal seafloor displacement observed in the 2011 Tohoku earthquake. Recent seabed mapping near the Japan Trench seems to support this hypothesis. Tappin et al. (2013) identified a large (~500 km3) landslide that explains the large run-up heights in the northern Honshu coast and high-frequency content of tsunami data that earthquake sources alone fail to explain.

In this work, we will extend the model of Ma and Hirakawa (2013) by incorporating coseismic landslides in the dynamic rupture model. Gravity needs to be explicitly considered in the formulation. We will use an updated Lagrangian approach in which the equation of motion, failure criterion, and boundary conditions need to be evaluated at the deformed reference frame. This approach should also allow us to incorporate tsunami propagation in a nonviscous ocean layer, which will make it the most complete model carrying information all the way from source to tsunami in a single code. Using this fully coupled model we will investigate the conditions for landslides, landslide styles (translational vs. rotational), and how inelastic wedge failure and landslides affect the arrival time, amplitude, and frequency content of tsunami waveforms.

From the Earthquake Source to Damage of Buildings: Bridging the Gap between Seismology and Earthquake Engineering

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3D Spontaneous Dynamic Rupture on Geometrically Complex Faults: the 2010 Mw 7.1 Darfield (New Zealand) Earthquake

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Field observations suggest that natural faults have a diverse degree of geometrical complexity such as branching and segmentations. Recent studies show that these non- planar geometrical complexities have dominant effects on the rupture dynamic process and near source ground motion. The 2010 Mw 7.1 Darfield (New Zealand) earthquake is one of the best recorded earthquake that exhibited geometrically complex faults, in which includes a vertical fault comprising bending and dipping branches. The rupture nucleates on a thrust branch fault and propagates on a strike-slip main fault with branches. We developed a 3D dynamic rupture model of this earthquakes considering its geometrical fault complexity. The unstructured 3D open source spectral element code SPECFEM3D is used for this investigation. This code allows modeling realistic non-planar fault geometries. Mesh generation software, CUBIT, is applied which employs hexahedral unstructured elements. Our simulations well describes the slip and rupture velocity from published kinematic source models obtained by source inversion. The role of the fault geometry on rupture dynamic process and stress changes and its effects on near-source ground motion is investigated.

Forecasting the Rupture Directivity of Large Earthquakes

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Forecasting the rupture directivity of large earthquakes is an important problem in probabilistic seismic hazard analysis (PSHA) because directivity strongly influences ground motions. In earthquake rupture forecasting, directivity depends on two probability distributions, the conditional hypocenter distribution (CHD) and the conditional slip distribution (CSD). The simplest CHD is a uniform distribution for which the hypocenter probability density equals the moment-release probability density. We use three methods to estimate the CHDs for a global set of large earthquakes: (a) location of hypocenters within the slip distribution from finite-fault inversions, (b) location of hypocenters within early aftershock distributions, and (c) direct inversion for the directivity parameter D, defined in terms of the degree-two polynomial moments of the source space-time function. Using method (c), McGuire et al. (2002) suggested a uniform CHD. The data from method (a), however, suggest a more 'centroid-biased' CHD; i.e., the directivities inferred from finite-fault models appear to be closer to bilateral than predicted by the uniform CHD. One source of this discrepancy may be centroid bias in the

second-order moments owing to poor localization of the slip in finite-fault inversions. We compare these observational results with CHDs computed from a large set of theoretical ruptures in the Southern California fault system produced by the Rate-State Quake simulator (RSQSim) of Dieterich and Richards-Dinger (2010) and discuss the implications for rupture dynamics and fault-zone heterogeneities.

Effects of Difference of Source Spectrum Modeling on Synthetic Motions in Empirical Green's Function Method

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The empirical Green's function method is one of the ways for predicting strong ground motions. This method synthesizes the waves induced by one-size smaller earthquakes than the earthquake we want to evaluate.

There are two kinds of source spectrum modeling, the crack model and the asperity model, and according to earthquake records, it is verified that both of the fault models have been observed in the past. That is to say, the suitable of the model can vary for earthquakes we want to predict.

In this paper, we investigated the extent of the effects caused by the difference of source spectrum modeling for the 2011 Ibaraki-oki earthquake (M_W 7.8), which is the largest aftershock of the 2011 off the coast of Tohoku earthquake (M_W 9.0). We examined it at four observation points, and as Green's function, we used observational ground motion data of earthquake of M_W 6.3 which occurred off the coast of Ibaraki.

We found that the synthetic waveform of ground accelerations or the durations of the synthesized motions were not affected by this inconsistency of the source spectrum modeling, and that there were no obvious difference between the pseudo velocity response spectra based on the crack model and those based on the asperity model in the period range of 0.1 to 10 seconds.

Also, we defined the synthetic ratio as an average of the quotients obtained by dividing each Fourier spectrum of synthetic waveforms by that of the element earthquake waveforms at each observation points. In the period range of around the corner period of (about Period 15 seconds), the synthetic ratio of the crack model was a little larger than that of the asperity model.

Quantifying the Spatial Variability of Ground Motion Residuals using Site-to-Site Closeness Index as a Distance Metric

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There have been many investigations into the spatial variability of residuals from empirically based ground motion prediction equations (e.g., Wang and Takada 2005, Goda and Atkinson 2010, Loth and Baker 2013). In this study, and in similar studies, spatial variability refers to the similarity (or dissimilarity) of ground motion residuals at different locations for a given event. Most studies quantify spatial variability in terms of semi-variance, autocovariance or autocorrelation. Regardless of the statistic used, spatial variability is almost always described as a function of linear distance between locations of observations as a metric of separation. In this study we use site-to-site closeness index as the metric of spatial variability of ground motion residuals. The site-to-site closeness index is a modified form of the closeness index (Lin et al., 2012)and is a measure of the similarity between the wave propagation paths of ground motion observed at two different sites for a given event. Our investigation is performed using three different regional data sets, one from Japan (Rodriguez-Marek et al. 2011), one from Taiwan (Lin et al., 2011) and one from California (Chiou et al. 2010). For each data set we calculated the semi-variance for two different kinds of ground motion residuals: intra-event residuals and single-station intra-event residuals. These calculations were performed for peak ground acceleration and pseudo spectral acceleration at 0.3 and 1.0 seconds. Results showa reduction in scatter when calculating the semi-variance as a function of site-to-site closeness index when compared to semi-variance calculated as a function of linear distance. This is observed for all ground motion intensity measures for all three regional data sets.

Progress Report for the Center for Engineering Strong Motion Data in 2014

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Strong-motion data from the US and other seismically active countries are served to engineers, seismologists, and public safety authorities through the Center for Engineering Strong Motion Data (CESMD) at www.strongmotioncenter.org. The CESMD is a joint effort between the USGS and the California Geological Survey, in cooperation with other US and international strong-motion networks. The CESMD benefits from ongoing cooperation with COSMOS (http://cosmos-eq.org), which assists in facilitating access to strong-motion data from other countries, and also provides advice on the development of user applications.

The CESMD now automatically posts strong-motion data from the California Integrated Seismic Networks as an Internet Quick Report within minutes following an earthquake. In response to engineering seismology needs in the US, strong-motion records from lower magnitude (<M3.5) and smaller amplitude (<0.5%g) records from CA are now provided at the CESMD FTP site for use in studies such as developing ground-motion prediction equations in areas with less frequent strong earthquakes. Metadata for strong-motion records from significant earthquakes in Japan with M6.0 or larger and depths shallower than 100 km that occurred from 2007 to 2013 have been uploaded to the Virtual Data Center (VDC).

One of the challenges in providing virtual access to strong-motion records is maintaining awareness of and responding to changes in data formats, file content, and file structures at cooperating networks. Following a re-organization of the data archives of the Japan K-NET and KiK-net, the CESMD and COSMOS successfully worked with the network operators to establish a new protocol for accessing these data. Virtual links to the records from the University of Nevada, Reno (UNR) network have been updated in the VDC database. Most recently, the CESMD has been working with the New Zealand GNS Science network to accommodate recent significant updates to their network data server and files.

Demonstration of PEER Record Processing Methodology

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During the NGA-West 2 and NGA-East projects the PEER processing methodology has expanded to be a comprehensive record processing (removal of unwanted noise) and time series metric calculator. The full documentation and code are in development with plans for a public distribution. This is to continue the transparency as promised in NGA-West 2 and to aid in more consistent time series processing and metric calculations in the research and engineering community. A demonstration of the methodology may include: 1) summary of to date allowable raw input formats 2) filter corner selection and review 3) windowing of various phases 4) summary of to date output time series metrics.

V/H from an Analysis of Kiban Kyoshin Network Data

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Vertical site response spectra used for seismic design are typically developed by applying a vertical-to-horizontal (V/H) ratio to the horizontal design spectrum. (See, for example, McGuire et al., 2001). V/H ratios have been developed based primarily on recordings at the ground surface but they often also depend in practice on some fundamental assumptions about differences in the effect of nonlinear behavior of subsurface materials on the upward propagation of vertically and horizontally polarized waves. Consequently, the currently used V/H ratios are directly applicable to surface V/H and, often, within the confines of these assumptions. Over the past decade more earthquake records from vertical arrays have become available. These new data can be used to determine how V/H ratios vary as a function of depth or, conversely, how, given an assumed V/H ratio at depth the V/H ratio at the surface might be estimated. A better understanding of the V/H ratio as a function of depth is also important for the design of deeply embedded structures.

We have analyzed data from available earthquake recordings from vertical downhole arrays of the Kiban Kyoshin network, a seismograph network which consists of pairs of strong motion seismographs installed at approximately 700 locations throughout Japan. The downhole depth for the network recording stations varies from 100 m to 3500 m. Many of the recording stations have P-wave and S-wave velocity profiles.

We calculate 5% damped acceleration response spectra and V/H as a function of frequency at the surface and at depth using these data. Our very preliminary

results show that V/H ratios at depths of 100m to 200m are generally higher than at the surface. Further investigations are being conducted to understand and quantify V/H at depth as a function of earthquake magnitude and site conditions/velocity, and these will be presented.

Nonlinear Seismology a Reality. Bridging the Gap between This Reality and Earthquake Engineering

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The authors developed in last time the concept of 'Nonlinear Seismology-The Seismology of the XXI Century'. Prof. P.M. Shearer, California Univ.:(i)-Strong ground accelerations from large earthquakes can produce a non-linear response in shallow soils; (ii)-The shaking from large earthquakes cannot be predicted by simple scaling of records from small earthquakes; (iii)-This is an active area of research in strong motion and engineering seismology. Aki: Nonlinear amplification at sediments sites appears to be more pervasive than seismologists used to think.Any attempt at seismic zonation must take into account the local site condition and this nonlinear amplification (Tectonophysics, 218, 93–111, 1993).The seismological detection of the nonlinear site effects requires a simultaneous understanding the effects of earthquake source, propagation path and local geological conditions. The authors used to study the free field response spectra which are the last in this chain and used in seismic design of all structures Analysis was conducted for last strong Vrancea earthquakes (March 04, 1977; Mw=7.5; h=94.5 km; August 30, 1986; Mw=7.1; h=134.5 km; May 30 1009; Mw=6.0; h=90.9 km; May 31, 1990; Mw=6.4; h=86.9 km). The amplification factors decrease with increasing the magnitudes of strong Vrancea earthquakes and these values are far of that given by Regulatory Guide 1.60 of the U. S. Atomic Energy Commission and IAEA Vienna. A characteristic of the nonlinearity is a systematic decreases in variability of peak ground accelerations with increasing earthquake magnitude. An example, spectral amplification factor decreases from 5.89 (Mw=6.4) to 5.16 (Mw=6.9) and to 4.04 (Mw=7.1) in Bacau seismic station. The analysis indicates that the effect of nonlinearity is very important and if the analysis is made for peak ground accelerations it is 45.7% smaller if we are considering linear soil respones at all and for stronger earthquakes it will be larger as value.

Ground Motion Hazard Maps for Engineering Design in the New Madrid Seismic Zone of the Central United States

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The New Madrid Seismic Zone is one of the most active seismic zones in the central United States and poses a certain level of seismic hazard and risk to the communities in the region. It is well known that the best way to mitigate seismic hazard or reduce seismic risk is better design and construction of buildings and infrastructures. However, selecting an appropriate ground motion for engineering design is challenging because it not only involves seismologists, but also engineers and other stakeholders. It is critical that seismologists not only produce ground motion hazard maps based on the best available science, but also clearly communicate the science to engineers and other stakeholders. It is also critical that engineers and other stakeholders understand the hazard maps correctly. Otherwise, the selected ground motion might not be appropriate for engineering design. For example, the ground motion hazard maps with 2 percent probability of exceedance (PE) in 50 years were selected for engineering design in the central United States. The maps are not consistent with the best available science and are difficult to understand. The use of these maps has caused problems in engineering design of buildings and infrastructure in the New Madrid region. Thus alternative ground motion hazard maps are needed. One such alternative map has been produced using a scenario or deterministic seismic hazard analysis. The scenario or deterministic ground motion hazard maps are scientifically sound and easy to understand.

Developing Worldwide Capacity for Analysis of Data Supporting Earthquake Hazard Analysis

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As part of its International Development Seismology initiative, IRIS has organized a series of 'Advanced Studies Institutes' (ASIs) in several locations recently—including Quito, Bangkok, Kuwait, and Santo Domingo—and each has included participants from numerous countries. The ASIs develop capacity to better use the wealth of new seismic data being collected in those regions for many purposes, and for seismologists in these regions to be more effective collaborators.

Each ASI includes hands-on learning experiences among the participants in topics closely related to seismic hazard mitigation, since this is the primary motivation for investment in seismology in low-income, earthquake-prone countries. The topics of study have included multiple event relocation methods for high-precision hypocenters, computation of centroid-moment tensors from regional data, and urban site characterization from analysis of ambient noise using several survey techniques.

Access to appropriate instrumentation is becoming more widespread but capability to manage and analyze data innovatively is less common. Each country from which our ASIs have drawn participants included practitioners with a wide variety of capabilities. All participants gain from opportunities to share their expertise in a structured setting, such as an ASI, in which software and instruction are provided, along with hands-on training.

Geographically-focused ASIs also provide opportunities to inventory seismological expertise in a region, to allow scientists who have similar interests and needs to become acquainted, and for students to identify potential research topics and opportunities to further their careers. Spurring international research collaborations can be an effective tool for developing capacity and motivating deeper involvement in the design and operation of seismic recording. The ASIs have resulted in data collection and analysis that are useful for appropriate investment to mitigate earthquake hazard.

The Effects of Local and Background Seismic Sources on the New Probabilistic Seismic Hazard Map of Peninsular Malaysia

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Even though Peninsular Malaysia is located in a low-seismicity region, the structures may be vulnerable to distant Sumatran earthquakes. Two seismic sources of Sumatra have been identified as the main contributors to seismic hazard of Peninsular Malaysia, namely the Sumatra fault and Sumatra subduction zone. In performing PSHA, the right lateral strike slip fault of Sumatra and the Sumatra subduction zone are divided into 21 segments. Historical earthquakes of this region, since 1900 up to 2013 are collected, analysed, and segregated according to the segments. The new recurrence rates of the modelled seismic sources are obtained based on the updated earthquake catalog using Gutenberg-Richter, Kijko and Sellevol, and Weichert methods. The PGA values on rock site of Kuala Lumpur (capital city of Malaysia) based on the historical earthquakes up to 2004, with 2 and 10 percents probability of exceedance were calculated as 149 gals and 74 gals respectively by Adnan et al. 2005. The updated seismic source parameters based on the new mentioned earthquake catalog (up to 2013) had somehow reduced a little bit the PGA values to 145 gals and 73 gals. With regards to the new earthquake catalogs, there are some earthquakes around Peninsular Malaysia that could not be assigned to any of the Sumatra seismic sources, and thus it could be understood that to achieve much more appropriate seismic hazard maps, a background seismic source should be considered for the region. Since 2007, several earthquakes due to local faults with the maximum moment magnitude of 4.0 are recorded in Peninsular Malaysia. Eventhough the local earthquakes were small, the epicenters were as close as 40 km to Kuala Lumpur, which could have remarkable effects on seismic hazard of the region. This study has attempted to employ the local and background seismic sources to consider their effects on the process of deriving the new probabilistic seismic hazard maps of Peninsular Malaysia.

CISN ShakeAlert: An Update on Earthquake Early Warnings from ElarmS

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Earthquake Early Warning (EEW) is the ability to detect an earthquake quickly and provide a few seconds of warning before destructive seismic waves arrive. The California Integrated Seismic Network (CISN) is operating a demonstration earthquake early warning system, called ShakeAlert, which includes delivery of earthquake alerts to potential users. With support from the Moore Foundation and the USGS, we have been improving the performance of ElarmS, the algorithm developed and operated by UC Berkeley, in terms of both reporting speed and accuracy. We are now operating ElarmS-2 or E2. Realtime seismic data are processed continuously at each of the California datacenters, UC Berkeley (UCB), Caltech, and USGS Menlo Park. The resulting parameters are passed to UCB for earthquake detection and characterization. Alerts are then sent to the ShakeAlert Decision Module and are published to test users from research, government agencies and some industrial partners. In the Bay Area, the rapid transit system, BART, is now slowing trains based on information from the EEW system. ElarmS is also running in the Pacific Northwest. We are now completing the implementation of GlarmS, a GPS module which will run continuously on GPS data to rapidly contribute estimations of magnitude and rupture length for very large earthquakes. Its input to early warning will be triggered by events from ElarmS. We have also invested considerable effort in developing and implementing assessment tools both for ElarmS, and for the overall ShakeAlert system.

Status of Earthquake Early Warning in Cascadia

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We present the current status of seismic and seismogeodetic earthquake early warning for the Pacific Northwest Seismic Network (PNSN) at the University of Washington in Cascadia. We have taken a two-stage approach to earthquake early warning: (1) detection and initial characterization using strong-motion data from the PNSN with the ElarmS package and (2) the triggering of geodetic modeling modules using GPS data from the Pacific Northwest Geodetic Array (PANGA) and combined seismogeodetic (GPS + strong-motion) data. The geodetic modeling modules include P_d magnitude scaling, PGD magnitude scaling, CMT and finite fault slip determination. Because of Cascadia's relatively low seismicity rate, and the paucity of data from plate boundary earthquakes there of any size, we have prioritized the development of a test system and the creation of several large simulated events. The test system permits us to: 1) replay segments of actual seismic waveform data recorded from the PNSN and contributing seismic network stations to represent both earthquakes and noise conditions, and 2) broadcast synthetic data into the system to simulate signals we anticipate from earthquakes for which we have no actual ground motion recordings. The test system lets us also simulate various error conditions (latent and/or out-of-sequence data, telemetry drop-outs, etc.) to explore how to protect the system from them. Finally, we report on real-time performance of the ElarmS system for small magnitude earthquakes between 2.5 and 4.5 and show few false alarms over a 9 month period and discuss challenges and future system design changes required for a more robust early warning system.

Real-time Seismogeodetic Monitoring of Structural Deformation during Shaketable Experiments

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Accurate low frequency strong motion recordings are important for understanding free field and building response in large engineered structures. We have developed a seismogeodetic monitoring system based on GPS technology for real-time observations of large earthquakes that can also be used for structural monitoring. The data analysis method implements real-time analysis of GPS and accelerometer observations in a tightly-coupled Kalman filter to provide absolute estimates of seismic acceleration, velocity and displacement. The technology is currently operationally streaming real-time observations from remote geodetic module packages at 17 GPS sites in southern California. The instruments were also installed and run in real-time on a four-story structure at the UCSD NEES shake table to test an inertial force-limiting floor anchorage system for seismically resistant buildings. Observations were made at five points on the roof of the structure, at the base, and at two nearby reference sites off the structure. We have compared observations made by three types of instrumentation: 1) Topcon and Trimble GPS geodetic receivers with an Episensor accelerometer, 2) GPS geodetic receivers with a MEMS accelerometer as implemented in the Geodetic Module instrumentation package, 3) Trimble NetR9 receiver with self-contained (RTX) real-time kinematic data analysis. This study complements our previous seismogeodetic study of the response of a four-story building to ground motions from the Denali fault earthquake, which shook the building to failure and produced measurable permanent displacement and tilt. This sequence of shaketable tests illustrates the potential for technology transfer and collaborative research on observed free field and building response using these unique measurements of low frequency absolute displacement, velocity, acceleration and tilt.

Cross Disciplinary Practices and Approaches to Assure Safety of Schools

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In no more than a heartbeat landscapes can be permanently altered by strong earthquakes. In 2002, Molise, Italy suffered a 5.7 Mw earthquake, killing 30, including 27 children. After more than one year, the town was still embroiled in legal battles with the government and engineers associated with the primary concern – the school collapse. The village of San Giuliano di Puglia was cordoned off and villagers were forced to take housing elsewhere while investigations went on. Daily, when security personnel changed shifts, villagers sneak into their village homes; retrieving favorite toys, personal items, books, precious memorabilia – restricted otherwise due to the controversy. Schools play an obvious, important role for us; primarily as education structures but also as important gathering locations for various community functions, and as go to places, shelters during disasters. Recent US disasters highlight pressing needs to examine other natural disasters to assess best practices, lessons learned, structural vulnerabilities and evacuation issues to evaluate those which may advance seismic safety of schools and protect communities. This is very important to optimize available resources, efficiently utilize federal and state funding, and assure that earthquakes remain on the US agenda as a potential high consequence event for Alaska, Western, Central US and other seismically active areas. Improvements to primary structural systems continue to be analyzed, designed and tested, as well as the nonstructural systems surrounding occupants in existing structures. Notable improvements must proceed in the use of materials for equipment restraint, strengthening of windows, HVAC systems, more innovative methodologies for exit and egress to aid occupants, all of which should be part of an evaluative, code-mandated process to assure safety of existing school buildings. Sadly, seismic uncertainty competes with government ability to responsibly appropriate needed resources.

SEISM Institute and SINAPS@ Project: Synergy between Scientists and Engineers in France to Improve Seismic Risk Assessment.

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CEA, EDF, CNRS, ECP and ENSC have gathered their expertise in seismic risk creating in 2012 the SEISM Paris Saclay Research Institute. The shared ambition is to build a reference cluster, developing tools and methodologies for modeling earthquake and its consequences on structures and equipments. SEISM conducts research with R&D organizations and academics, technical support of regulators and industry. SEISM hosts researchers and PhD students, organizes trainings and teachings. During the process of SEISM Institute building, the 2011 Tohoku earthquake and associated tsunami occurred, causing severe nuclear accidents at the Fukushima Daiichi Nuclear Power Plant, where level 7 (Ines scale) meltdown

at 3 reactors occurred. Although no nuclear facility exhibited any failure related to seismic vibrations the underestimation of the seismic and tsunami hazards have been recognized by the Japanese community and should indeed be a concern for the world community. Within this framework, SEISM built an ambitious 5-year research project called SINAPS@. Now funded by the French national research agency, SINAPS@ aims at exploring the uncertainties associated to databases, physical processes and methods used at each stage of seismic hazard and structural and nuclear components vulnerability assessments, in a safety approach: the ultimate objective is to identify and quantify the seismic margins associated to a given seismic design level and a design strategy. SINAPS@ brings together a multidisciplinary community of researchers and engineers from 7 academic teams and 5 organizations associated with nuclear issues, 13 Ph.D. theses and 15 post-doctoral researchers. While such an integrative approach has been already considered in a number of institutes and projects throughout the world, SINAPS@ stands as the first research project in France explicitly attempting to fully assess the seismic risk from the fault up to the civil engineering and equipments, focusing on uncertainties.

Seismic Response of Building Clusters: A Numerical and Laboratory Study.

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The study of coupled resonances and local effects in a cluster of buildings excited by a seismic source may add important constraints to the cluster's layout design, highlight differences with respect to isolate buildings and to help predicting maximum acceleration. Through numerical simulations and laboratory experiments based on the analogy between acoustic meta-materials and cluster of buildings, we show how the seismic response of the cluster can be studied starting from a reduced sets of parameters on models scaled to the acoustic frequency range. Acoustic meta-materials establish a novel class of materials whose realization embeds sub-wavelength resonators, i.e. resonating elements whose characteristic size is much smaller compared to the wavelength. We have realized an experiment allowing the study of the effects that these objects have on elastic waves, which is of strong interest in seismology. The experiment reveals that when excited by an acoustic or a seismic source, meta-materials may give rise to (1) band-gap effects, i.e. frequency bands in which seismic energy does not propagate, or (2) sub-wavelength focusing, i.e. energy conversion on wavelengths much smaller than the original propagated signal. Inspired by these results we have modeled numerically 3D configurations, which include variable building/resonator sizes and distributions, a layered half space, and double couple seismic sources. The analysis presented addresses mainly two problematics. (1) For each configuration, it is shown the distribution of the energy within the cluster highlighting the maximum vertical and horizontal acceleration. In the case of a uniform size and distribution of the buildings characterizing the cluster, the insertion of a shorter building results in a strong focalization on this latter. (2) It is investigated the possibility of using band-gaps to realize seismic free configurations or to isolate determined buildings with respect to their resonance frequencies.

Near-Field Seismoacoustics of Natural and Man Made Explosions

Poster Session · Friday · 2 May · Cook/Arteaga

Hydroacoustic Recordings of Explosive Submarine Eruptions at NW Rota-1 and West Mata Volcanoes

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Because they are remote and difficult to access, relatively little is known about the nature of explosive submarine eruptions. Only two deep (> 500 m) submarine volcanoes have been observed in eruption: NW Rota-1 volcano (Marianas), and West Mata volcano (Lau Basin). NW Rota-1 was observed to be erupting from 2004–2010, and West Mata's eruption was observed between 2008–2010. Video footage shows that both eruptions include repeated bubble bursts and lava extrusion largely driven by magmatic degassing. Here we present data recorded during the two eruptions by moored hydrophones. At NW Rota-1, a single hydrophone was moored within a few hundred meters of the active vents. The West Mata eruption was recorded by four hydrophones suspended in the SoFAR channel between 5–20 km from the volcano.

The volcanoes exhibit several distinct hydroacoustic signals: (1) discrete, high frequency (10–200 Hz) bursts with durations of <1 second, (2) cyclic, diffuse, broadband signals that begin and end abruptly and last from seconds to 10's of minutes, and (3) continuous, narrow-band tremor at ~2–5 Hz. The high frequency signals are interpreted to be individual gas explosions similar to those observed infrasonically at volcanoes such as Stromboli, Karymsky, and Shishaldin. West Mata's discrete explosions occur at irregular intervals while those at NW Rota-1 are generally very evenly spaced, often resulting in a strongly harmonic spectrum. There are no clear source harmonics in the signals recorded at West Mata, although interference of direct and surface reflections at the hydrophones results in spectral bending (Matsumoto et al., 2011). Many of the West Mata broadband signals also have a strong monochromatic band at frequencies ranging from 50–200 Hz. This signal was not observed at NW Rota-1 in 2009, but occurred in 2010 after the eruptive vent had been modified by a major landslide. This suggests that different vent geometries have distinct hydroacoustic character.

Acoustic Signatures of Different Explosive-Detonator Configurations in Small HE Explosions.

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We are analyzing seven 11-kg HE detonations to identify acoustic signatures related to the position of the detonator in the explosive material. The explosions were conducted at a height of burst of 4m, the explosives were 8-inch cylinders with the detonator pointing at different directions (South(2), East(2), up(1), and down(2)). The data is comprised of high speed video (3000 fps) recorded in the vicinity of the explosion (< 200m) and overpressures recorded at 0.87 km radial distance from the source using a high sampling rate (25Ksps) recorder with a broadband microphone with flat response between 10 Hz and 20 KHz. Additional instrumentation includes low frequency recorders (<1KHz) using infrasound sensors and nearby weather towers.

An Analysis of Repeating Explosions using Seismoacoustic Data

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We present a summary of recent explosion experiments at Los Alamos National Laboratory (LANL) designed to understand the effects of explosion configuration and yield on seismoacoustic signatures. By performing repeated experiments, we are able to explore the variability of source and path in a statistical way. Source effects comprise a variety of yield, height-of-burst, and ground effects. Path effects are explored using meteorological towers and topographical profiles for each source-receiver path.

The Acoustic Signatures of Ground Acceleration, Gas Expansion, and Spall Fallback in Experimental Volcanic Explosions

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Results from an infrasound array deployed during an experimental volcanology initiative shed new light on the sources of acoustic emissions during a buried explosion. Acoustograms of each explosion contain information on the magnitude of initial ground deformation, the contribution of gas breakout to the total amplitude of the signal, and timing of the fallback of displaced material. The presence and relative amplitudes of these three phases varied based on the size of the explosive charge, the burial depth, and whether or not the substrate had been disturbed by previous blasts. The amplitude of the acoustic pulse from ground deformation closely matched the observed ground acceleration of the blast region determined using particle image velocimetry. The arrival of the gas release phase corresponded with the timing of gas breakout at the ground surface as observed using high speed video. The ground fallback signal obeyed the relationship between time

delay and explosion size as outlined in Lee and Walker (1980). Similar amplitudes and waveform characteristics were observed on the ground and on an airborne array held aloft by helium balloons, indicating that the radiation pattern was isotropic. We describe a conceptual model for the acoustic signals generated by buried explosions based on the results from this experiment and literature on subterranean nuclear explosions. Finally, we place recent observations of ground deformation induced acoustic signals at Santiaguito volcano, Guatemala and Sakura-jima volcano, Japan, in the context of this model.

Large Scale Blast Experiments Integrate Field, Remote Sensing, and Laboratory Based Techniques

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Many problems in Geophysics arise from complex scaling behavior, and therefore bench top studies cannot be used to appropriately investigate all mechanisms critical for scaling to natural scenarios. Such inversion problems are addressed at the Geohazards Field Station (GFS), a user facility hosted by University at Buffalo, by setting up larger than bench top, free air experiments which can include much more natural complexities. The experimental scale also allows to monitor the process with remote sensing equipment and investigate using standard geologic techniques.

For this purpose the GFS was used to conduct crater-forming experiments using chemical explosives (Pentex booster charges, 1–3 10^6 J) as driving energy source. The experiments were designed to study explosions which occur during the formation of maar volcanoes, and during the interaction of groundwater and magma, where multiple explosions take place at similar locations, close and far from the surface. However, they have been useful to highlight more universal behavior in subsurface explosions. The blasts created craters up to 2.7 m diameter and were monitored by a diverse set of sensors including high-speed, high-definition, and thermal cameras, microphones, infrasound microphones, electric field sensors, seismometers, geophones, high-frequency seismic sensor, and a pitot tube. The availability of data observing the dynamics of crater formation, and the static final products is a unique opportunity to better understand this process. Integrating the diverse sensor data and geologic records helps to interpret the sensor signals and map their individual parts to process phases, states and end members of a blast. The experiments serve as an excellent base for interdisciplinary meeting point, equipment testing, and student training.

A Seismo-Acoustic Infrasound Methodology for Accurate Large Scale Simulations

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We present recent progress towards a coupled seismo-acoustic simulation capability. This work aims to improve the modeling of energetic events that trigger mechanical waves that propagate through both the solid earth and the atmosphere.

Acoustic wave propagation can be modeled by solving the linearized Euler equations for compressible fluid flow. The acoustic waves are modeled as small perturbations on top of a given background velocity, pressure, and density field, which may vary in space. Acoustic waves are advected by the wind, which can cause significant bias in sound propagation, and modify the refraction of energy compared to a calm atmosphere. Because of advection, the acoustic wave equations are naturally formulated as a first order hyperbolic system (i.e., containing up to first derivatives in space and time). This system is written on symmetric form, and then discretized by a high order accurate finite difference scheme that satisfies the principle of summation by parts (SBP). Using the symmetric form of the governing equations allows an energy estimate to be derived through integration by parts. By applying similar operations on the SBP difference approximation, a discrete energy estimate can be derived, implying stability of our finite difference discretization of the acoustic wave equation. This approach generalizes to curvilinear coordinates, allowing effects of realistic topography to be taken into account.

The acoustic modeling capability will be coupled to our current parallel seismic modeling code SW4, which implements a 4th order accurate SBP scheme to simulate 3-D seismic wave propagation in a heterogeneous viscoelastic material, satisfying the free surface boundary condition along realistic topographies. The acoustic and seismic domains will be coupled by imposing continuity of traction and normal velocity along the solid-air interface.

New Directions in PSHA: Ins, Outs, and Uncertainty

Poster Session · Friday · 2 May · Cook/Arteaga

Empirical Hazard Curve Constraints Using Precarious Rocks of Southern California

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Precariously balanced rocks (PBRs) are naturally occurring geologic features susceptible to toppling if exposed to moderate or strong strong ground motions. Where they occur PBRs thus provide an upper estimate of ground shaking. Ground motion constraints from PBRs are most important at return times long compared to the instrumental record. A standing issue of using PBRs has been a limit on the number of them having quantitative estimates of toppling ground accelerations. Field testing and/or 3D photographic modeling is expensive and has been done for a relatively few rocks. We have largely overcome that difficulty by using a 2D photograph-based method that gives reasonable, though less certain, estimates of toppling acceleration, but takes only a few minutes per rock. With this advance, the archive of PBRs in southern California is now sufficiently mature to be able to propose an empirical hazard curve hazard as a function of distance from the area's active faults. As a fault database we used the fault sources of the 2008 National Seismic Hazard Map. When considered together, we find a clear distance dependence in PBR survival. Within 5 km of active faults, rocks that would topple at 0.35g become rare, while at 20 km, this threshold decreases to about 0.25 g. These levels are similar to median ground motion prediction equation (GMPE) expectations for hard rock sites, which indicates that PBR site conditions are not exceptional. We also find little dependence on fault slip rate. This is somewhat unexpected because high slip rate faults generally produce more earthquakes during the fragile lifetime of the rock, and thus more opportunities to exceed median ground motions. Thus the PBR data suggest that variability in ground motion from event to event may be low for southern California faults. This tends to confirm the earlier assessment by Anderson and Brune (1999) that the ergodic assumption for ground motion will overstate variability.

A New Perspective towards the Generation of Response Spectral Ground Motion Prediction Equation for Seismic Hazard Analysis

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Adjustment of empirically derived ground motion prediction equations (GMPEs) to different seismological conditions is one of the major challenges in engineering seismology and seismic hazard studies. In the present study we propose a new and physically consistent framework for the development of a response spectral GMPEs which can be easily adjusted to different seismological conditions; and which does not suffer from the practical problems associated with adjustment in the response-spectral domain. The approach we present brings together two different paradigms of ground motion modeling. The first component, as described in its initial form by Bora et al. (2013), consists of an empirical FAS (Fourier Amplitude Spectrum) model and a duration model which are combined within the random vibration theory (RVT) framework (Boore, 2003) to obtain the full response spectral ordinates. In addition, we extrapolate the observed FAS beyond the frequencies which are supported by the observed acceleration records using stochastic FAS models, obtained by inversion as described by Edwards and FAh (2013). This way we obtain response spectral models which are easily adjustable to different sets of seismological parameters such as stress parameter, kappa values, t* values, etc. We present this analysis for the recently compiled strong-motion database RESORCE-2012 obtained for data from Europe and the Mediterranean region.

Event Terms for the Shallow 2011 Normal Faulting Earthquakes in the Ibaraki – Fukushima Prefectural Border Region, Japan

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In the global database of strong earthquake ground motions, there is considerably less data for large normal faulting events in the shallow crust than for events with strike-slip and reverse mechanisms. After the Mw9.0, 2011 Tohoku, Japan earthquake, a sequence of very well recorded normal faulting events occurred on land. The largest event, the Mw 6.6 Fukushima-Hamadori earthquake, caused surface faulting with up to 2 meters of vertical slip. These events greatly expanded the amount of strong-motion data for earthquakes with normal mechanisms, but occurred too late to be included in the 2013 updates of the NGA ground motion prediction equations. Anderson et al. (2013) found that the ground motions during the largest event were large compared with the 2008 NGA relations. This paper compares all 13 earthquakes in the sequence with Mw greater than 5.0 with the 2013 NGA relations. We applied the site-specific station corrections of Kawase and Matsuo (2004) to the raw data, as was done by Anderson et al. These corrections significantly reduced the variance compared to the raw data. For PGA and PGV we found event terms, i.e. the average of the residuals, ln(observed/NGA model), based on data within 100 km of the fault. While comparisons depend on the specific model, some general trends appear in our preliminary comparisons. For PGA, the event terms are near zero or positive at lower magnitudes (Mw under 6.0), and positive at higher magnitudes. For PGV, the event terms are positive at all magnitudes. For most comparisons, the residuals increase with distance; the slope of this distance dependence is greater for the lower magnitudes for both PGA and PGV. Our ongoing study aims to extend the results to more points on the response spectrum, and reconsider the site-response corrections.

Memphis Urban Seismic Hazard Mapping Update: New Geology Plus Shear-Wave Velocity and Earthquake Observations

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In 2012–2013 the Memphis urban seismic hazard maps were updated with an improved and expanded geology model covering all of Shelby County, Tennessee. The new geology-only model predicts fairly uniform ground motions on the Shelby County uplands (PGA ~0.3 g for M7.7) but lower ground motions on the western lowlands (Mississippi floodplain). Differences in ground motions are mostly related to alluvium/loess thickness variations, which have an assigned shear-wave velocity (Vs) less than 200 m/s. Vs-profile observations across Shelby County (Romero and Rix, 2001) show Vs < 200 m/s consistently to depths of only ~10 m, unlike the geology-only model's of ~20 m in the NW uplands and greater than 30 m in the lowlands. A new geology plus Vs model shows more uniform hazard across the uplands and lowlands. We check on the reality of the new geology plus Vs based hazard estimates using two recent earthquakes: the 10/29/2012 M3.6 Parkin, AR west of Memphis and the 02/21/2012 M3.9 East Prairie, MO to the north. Scenario ground motion models for these two earthquakes show the greatest difference between the geology-only and geology-plus-Vs models in the lowlands and mainly for long period (1.0 s). A residual analysis at 9 ANSS stations across Shelby County for these two earthquakes favors the geology-plus-Vs model. This comparison helps validate the shallow Vs model over the shallow geology model. The ultimate validation will come from future stronger motion observations that demonstrate a similarity or difference in ground motion between the lowlands and uplands in Shelby County.

Magnitude Dependent Site Amplification Seismic Hazard Calculation Outside the Hazard Integral for St. Louis, MO

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Richard Lee (2000) developed an approach to site-specific seismic hazard calculation for magnitude-independent site-amplification that applies the site amplification distribution outside the hazard integral. Cramer (2009b) implemented this approach for urban seismic hazard mapping in St. Louis, MO-IL. However, the USGS National Seismic Hazard Mapping Project deaggregation for St. Louis shows that the predominant hazard is from M7s about 200 km from the study area and M5s and M6s within 50 km of the study area. Cramer (2009a) developed site amplification distributions corresponding to these three levels of magnitude and corresponding distance and showed that the M7 at 200 km case is different from the M5 and M6 < 50 km cases. Hence site amplification is magnitude dependent in the St. Louis area.

Richard Lee (2010, oral communication) suggested that the magnitude-dependent site-amplification problem could be divided into a series of magnitude-independent site-amplification calculations over limited magnitude ranges. The hazard curves from the series of outside the hazard integral calculations for different magnitude ranges could then be combined for the total hazard curve at a site or grid-point. This magnitude dependent site amplification approach has been implemented, tested, and applied to generating St. Louis urban seismic hazard maps. The outside the hazard integral approach for applying site amplification distributions is more computationally efficient (5–10 times faster) and separates the tasks of hazard and site amplification calculation so a change in one does not force the recalculation of the other as the inside-the-hazard-integral approach requires (Cramer, 2003, 2005).

Seismic and Tsunami Hazard Assessment in the Southwestern Hellenic Arc based on Multidisciplinary and Multiscale Geophysical Data – The EU SEAHELLARC Project

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Aim of the SEAHELLARC project was to develop a new approach in assessing seismic and tsunami hazard by exploiting new hardware and combining geological, geophysical and engineering research. The coastal zone of western Peloponnese, south western Hellenic arc, was used as a pilot area, as this margin is one of the most seismic and tectonic active regions of Europe. The most important achievement of the SEAHELLARC project was the integration of multidisciplinary and multiscale geophysical data (from seabed to deep crust and upper mantle) to better understand the structure, tectonic and geological hazards on an active margin. Seismic hazard was computed according to the most updated approach (the logic tree approach, that incorporates all uncertainties involved in the computation) and considering a new seismogenic zonation, established during the SEAHELLARC project on the basis of the results of passive and active experiments. Moreover, the seismic sources that have generated or could generate tsunami were identified and characterized from the geographical and seismic point of view.

Results of a Preliminary Earthquake Hazard Study in North Baja California, Mexico

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In the last decades several earthquakes of magnitude larger than 6 occurred in the Baja California-Southern California region. Most recently, the El Mayor-Cucapah earthquake of April 4, 2010 (M 7.2) produced severe damage along the eastern part of north Baja California. Its strong motion effects were our main motivation to start a seismic hazard assessment for the region. Here, we present the first preliminary results of a hazard analysis that is presently underway. For the hazard computations, a computer code that is based on Matlab programming language was developed. Validation of such computer program was done through satisfactory reproductions of results of a benchmark PSHA example (Kramer, 1996) and of other published results. The preliminary results of runs of this program are shown in maps with contour lines of peak ground acceleration (PGA) and spectral acceleration (PSA) in 2% and 10% exceedance probabilities in 50 years. To get the hazard results, all major faults of the area were considered as seismic sources, and each source was modeled as a Poisson earthquake process, for which the magnitude – frequency relation was a truncated Gutenberg–Richter curve. The a- and b-values for each source were estimated from regional catalogs containing the seismicity of the last 35 years. On the other side, the ground motion levels for given magnitudes and source-to-site distances were obtained from the NGA attenuation model of Boore and Atkinson (2008) or from a model by Boore et al. (1997). In addition to the above hazard maps, we also show maps with results of hazard disaggregation computations. Displays of the contributions to hazard in terms of the geographic coordinates provide a better insight about the most probable scenarios for specific sites.

A UCERF3-Based Seismic Source Model for the Lawrence Livermore Laboratory Region, California

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A seismic source model was developed for the Lawrence Livermore Laboratory site, southwest San Francisco Bay Area, California. Due to the proximity of

active seismogenic features near the site and deaggregation of previous hazard results, only sources within 100 km were considered, with emphasis on sources within 40 km. Fault characterizations were adapted from the recently released UCERF3 model. This model has several advantages over previous ones, including increased attention to, and rational characterization of, multi-fault ruptures, and increased utilization of geodetic data and aseismic factors. The magnitude-frequency distributions (MFD) that resulted from the UCERF3 inversion were used as primary inputs to recurrence rates for the modeled fault sources. The MFD for a fault contain multi-segment ruptures that are also contained in those for adjacent, participating faults. To avoid double counting, a scheme was developed to subtract the rates of these multi-segment ruptures from participating faults that are not closest to the site. Several faults in close proximity to the site which were not included in UCERF3, such as the Livermore Anticline, Springtown Anticline, and Williams-Verona faults, were added to the model. Background, or off-fault seismicity was characterized by using the UCERF2 grids. While the UCERF3 model weighted new UCERF3 grids equally with the previous UCERF2 grids, analyses shows them to contribute equally to the hazard in the Livermore area.

Seismic Source Characterization (SSC) Approaches for a Site-Specific PSHA Controlled by Fault Sources: The Diablo Canyon Power Plant Seismic Hazard Update, Central Coastal California

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Pacific Gas & Electric Company (PG&E) is performing a seismic hazard update for the Diablo Canyon Power Plant (DCPP). Seismic hazard at the DCPP site, located on the central California coast, is dominated by nearby fault sources including the offshore Hosgri-San Simeon-San Gregorio strike-slip fault system and a series of intersecting strike-slip and reverse faults that branch eastward and extend onshore. The recently released UCERF3 poses a challenge to the traditional fault characterization strategies that have been used in a regulatory environment. UCERF3 replaced segmentation-based fault models with a quasi-continuum model that allows ruptures of almost any length up to the full length of the fault system. It also allows multi-fault ruptures, so short faults near DCPP are allowed with some probability to link with long faults like the Hosgri. Assigning meaningful probabilities to the complete set of possible ruptures would be impractical. Instead, the revised seismic source model for DCPP is incorporating UCERF3 concepts, within a traditional PSHA framework, in two main ways: first, by shifting emphasis from epistemic (model) uncertainty in total fault length and segmentation to aleatory (natural variability) uncertainty in rupture sources on the network of fault sources near DCPP; and second, by incorporating magnitude-frequency distributions that allow both characteristic earthquakes informed by local fault length scales and maximum earthquakes informed by total lengths of fault systems. A current challenge to this approach is to devise a defensible partitioning of seismic moment for hazard estimation between classic local fault ruptures and larger allowed ruptures, the frequency of which is virtually unknown. The DCPP SSC is also introducing a new approach in which limits on fault geometry and slip are correlated through a set of tectonic models, with the goal of keeping fault uncertainties bounded by mechanical consistency.

Hazard Implementation of Simplified Seismic Source Characterization Allowing for Linked Faults

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The magnitude-frequency distributions (MFDs) commonly used for fault-specific sources in probabilistic seismic hazard analysis (PSHA), such as the characteristic magnitude distribution of Youngs and Coppersmith (1985) or the maximum magnitude model of Wesnousky (1986), specify the frequency of earthquakes up to a fixed upper limit that is typically defined based on the specification of a segmentation model for the fault. Characterization of interacting faults with possible multiple segment linkages in less frequent very large ruptures requires specification of the relative frequency of each rupture scenario included in the hazard model that has been specified either by expert assessments coupled with seismic moment balancing (e.g. the Working Group on California Earthquake Probabilities, 2003) or by large-scale inversions of geological and geophysical data (e.g. UCERF3).

To facilitate the incorporation of the concepts of potential fault segment linkages in standard PSHA studies we propose a generalized MFD that captures the characteristic magnitude behavior of the standard models while allowing for rare, large magnitude, linked ruptures. As described in Wooddell and Abrahamson (2013) the shape of the MDF is based on forward modeling of the coefficient of variation for slip at a point that is consistent with the global dataset of Hecker et al. (2013). Coupled with an assumption that the average slip over the full rupture is the same as the average slip on the segment closest to the study site, we now demonstrate a simplification to the moment balance by only tallying the fraction of the moment released on the nearest segment; thus only the nearest fault segment requires full characterization. Utilizing the new PDF and our simplified moment balance approach, we explore the hazard implications of this model and sensitivity to the selection of magnitude-displacement relationships, models for the probability of surface rupture, and other PDF model parameters.

Rupture Synchronicity in Complex Fault Systems

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While most investigators would agree that the timing of large earthquakes within a fault system depends on stress-mediated interactions among its elements, much of the debate relevant to time-dependent forecasting has been centered on single-fault concepts, such as characteristic earthquake behavior. We propose to broaden this discussion by quantifying the multi-fault concept of rupture synchronicity. We consider a finite set of small, fault-spanning volumes and identify the discrete event times at which each volume participates in a rupture above a magnitude threshold. The main object of our analysis is the complete set of event time differences, which we take to be a random process with an expected density function. We call this function the auto-catalog density function (ACDF) for a single volume and the cross-catalog density function (CCDF) between separate volumes. For a renewal process, the ACDF can be written in terms of convolutions of the interevent-time distribution, and many of its properties (e.g., large-t asymptotes) can be derived analytically. Synchronicity can therefore be characterized by the variability of the CCDF about this asymptote. We preform this analysis on a million-year California catalog generated by the RSQSim earthquake simulator. At interseismic (Reid) time scales, we observe pairs of fault segments that are tightly locked, such as the Cholame and Carrizo sections of the San Andreas Fault (SAF); segments out of phase (Carrizo-SAF/Coachella-SAF and Coachella-SAF/San Jacinto), where the CCDF variation is an odd function of time; and segments where events are in phase with integer ratios of recurrence times (2:1 synchronicity of Coachella-SAF/Mojave-SAF and Carrizo-SAF/Mojave-SAF). Therefore, despite its geometrical complexity and multiplicity of time scales, the RSQSim model of the SAF system exhibits a variety of synchronous behaviors that increase the predictability of large ruptures within the system.

Estimating and Utilizing the Space covered by GMPEs for PSHA

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To capture the range of epistemic uncertainty in probabilistic seismic hazard analysis, different models are combined in a logic tree framework. An important aspect in this context is the number of branches, i.e. the number of models that should be employed, and whether they cover the expected range of epistemic uncertainty. There are many published ground-motion prediction equations (GMPEs) which can potentially be used in a PSHA. Each of these models can be thought of as a point in a high-dimensional model space. However, due to physical constraints this model space cannot be arbitrarily shaped, but forms a lower dimensional manifold. Using visualization tools such as e.g. self-organizing maps, we estimate this manifold. From the resulting visualization we generate new models, effectively interpolating between existing GMPEs along the manifold. This allows us to enhance the set of available models in a structured, physically driven way. The newly generated models are an estimate of the full ground-motion distribution covered by the employed GMPEs. Generating visualizations from subsets of models and subsequently adding

models, we investigate how many models we need to obtain a stable visualization, i.e. a stable estimate of the lower dimensional manifold. In particular, we check whether the left-out GMPEs are covered by the visualization, i.e. if they can be recovered by a model generated from the visualization. Thus, we can determine a sufficient number of GMPEs for the logic tree. Finally, we discuss how the visualization, and the space each model occupies within it, may aid in choosing logic tree weights.

Between-Event Uncertainty for "Repeating Earthquakes"

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Recent studies of strong ground motions have placed increased importance on understanding the uncertainties in ground motion predictions. Ground motion prediction equations (GMPEs) often separate the between-event (tau) from the within-event variability, but recent studies have focused on more precise distinctions, such as single-station sigma.

The concept of a fault that ruptures identically in repeated events was called a characteristic ground motion earthquake by Anderson and Brune (1999). An extension of this idea to observations suggests that perhaps the smallest uncertainty that can be expected in ground motion recordings is to be expected when the same station records motion from rupture of the same fault segment in repeated events. We have searched for records from repeated rupture of the same fault in similar, large-sized earthquakes ($M > 5$), and found several cases, two of strike-slip faults from the US and five of thrust faults from Japan, which in our judgment are similar enough that the differences in ground motion are relevant to estimating the uncertainty due to the variability of multiple ruptures of a single source. We compare the 5% damped spectral accelerations for these events at the recording stations, and calculate the maximum-likelihood standard deviation $\mathrm{tau_{ep}}$ within a pair. For period ranges where records from both earthquakes are reliable, we find that $\mathrm{tau_{ep}}$ averages between 0.1 and 0.2 natural log units. Based on extensive numbers of synthetic seismograms with random variability, we find that the actual value of $\mathrm{tau_{ep}}$ is larger by a factor of 1.76 compared to the maximum likelihood estimates using event pairs. This suggests that the variability from repeating earthquakes is 0.18-0.36, which is comparable or lower than tau estimated in GMPE studies.

Straightforward Bayesian Procedure for Estimation of the Regional Characteristic, Maximum Possible Earthquake Magnitude m_{max}

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Upon investigations into the mathematical structure of the currently used Bayesian procedure for the estimation of the regional characteristic, maximum possible earthquake magnitude m_{max} (Cornell, 1994), a mathematical flaw was discovered which results in the biased assessment of m_{max} (Kijko, 2012). The degree of the bias and its sign depend on the applied Bayesian estimator, the quantity of information provided by the prior distribution and the sample likelihood function. It has been shown that if the maximum posterior estimate is used, the bias is negative and the underestimation of m_{max} can be as big as 0.5 magnitude units. The cause of the problem lies in the properties of the sample likelihood function for which the range of observations (earthquake magnitudes) depends on the unknown parameter m_{max}. This dependence violates the property of regularity (LeCam, 1970) of the maximum likelihood function. The possibility to modify the current Bayesian procedure through the replacement of the 'incorrect' sample likelihood function with a seismicity-driven distribution of m_{max} is explored. The Monte-Carlo simulations show that the newly proposed approach is surprisingly very efficient and is capable of providing correct values of m_{max} even when a low number of seismic events are available.

References

Cornell C.A. (1994). Statistical Analysis of Maximum Magnitudes. EPRI, Palo Alto, Calif. 1994; NP-4726: 5-1–5-27.

Kijko A. (2012). On Bayesian Procedure for Maximum Earthquake Magnitude Estimation. Research in Geophysics, 2:e7, Number 1. http://www.pagepress.org /journals/index.php/rg.

LeCam L. (1970). On the Assumptions Used to Prove Asymptotic Normality of Maximum Likelihood Estimates. Ann. Statist., 41, 802–828.

Maximum Possible Earthquake Magnitude: Limits of Inferences from Longterm Data in the Framework of the Poisson Model

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In recent publications, it has been shown that earthquake catalogs are useful to estimate the maximum expected earthquake magnitude in a future time horizon T_f. However, earthquake catalogs alone do not allow to estimate the maximum possible magnitude $M(T_f \to 8)$ in a study area, unless strong prior assumptions are made. Assuming independent magnitudes drawn from a truncated (or tapered) Gutenberg-Richter distribution, optimal estimates of M (or the corner magnitude) depend solely on the largest (or few largest) observed event(s) regardless of all the other details in the catalog. Therefore, instrumental earthquake catalogs provide only little information on M, even if they include a huge number of small and intermediate events. In this study, we focus on the question, whether other data might be helpful to better constrain M. Assuming a Poisson process for earthquake occurrence, we show that the maximum observed magnitude μ_T in a known time interval T in the past (historic or paleo-earthquake) provides the most powerful information on M in terms of the smallest confidence intervals. Other data are less powerful, because they either correlate with earthquake catalogs (e.g. deformation from GPS records), or act as earthquake proxies introducing additional uncertainties (e.g. strain rates from geological assessments). The only strategy to achieve a higher information gain from longterm data with respect to the estimation of M is the replacement of the Poisson assumption by a different model for earthquake occurrence.

Preliminary Precariously Balanced Rock (PBR) Age Dates Based on Various Models of Erosion

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The fragility and age of precariously balanced rocks (PBRs) are critical in constraining PSHA results. We present preliminary estimates of PBR ages based on preliminary 10Be concentrations provided by Dylan Rood (Rood et al., SRL 2010; EOS 2012). We consider increasingly complex models for erosion: (1) Instantaneous exhumation followed by a number of years of exposure (CRONUS), (2) Constant erosion rate of a flat surface from far above the rock to the time of exposure of the rock pedestal, (3) the 4 parameter model (3 erosion rates and age of the lowest sample on the pedestal) of Balco et al. (Quat. Geochron., 2011), and (4) a model similar to that of Balco et al., but with a tilted erosional surface. We have made corrections for paleo-intensity, improved shielding (5 deg by 5 deg sampling, and the effective attenuation length). Similar to Balco et al., we ran tests to fit 10Be concentration profiles for 5 PBRs, using 4 to 8 samples per PBR.

In all cases the resulting pedestal age is at least a few thousand years. The pedestal age is a proxy for the elapsed time since the rock became precariously balanced. As pointed out by Balco et al (2011) various parameters in their model (and in our new models) are uncertain and could lead to changes in pedestal ages, but in no case could we get age dates less than a few thousand years. Results are similar to those found by Bell et al., (Geology 1998) using 36Cl, and by Purvance et al., (SCEC 2009) using varnish microlamination dating (VML).

Testing UCERF3

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The third Uniform California Earthquake Rupture Forecast (UCERF3), is a complicated model. However, it forecasts prospectively testable outcomes: rates of on-fault earthquakes, rupture geometries and magnitudes, and spatial density rates of off-fault earthquakes. One version of the model includes explicit time dependence of the rates. As with the previous UCERF2, the epicenters of on-fault earthquakes can be converted, with a few assumptions, to spatial densities as well, resulting in an epicentral rate density as a function of magnitude and location. This type of forecast can be tested against other forecasts based on various methods such as strain rate and smoothed seismicity using methods developed and practiced by the Collaboratory for Study of Earthquake Predictability (CSEP). But UCERF3 includes many features not well represented in the ongoing CSEP tests. Most important, CSEP has focused on tests that can be resolved in times less than 5 years, and important features of UCERF3 include thousands of specific large on-fault ruptures with recurrence times of centuries or longer. Testing the rates of such events individually is out of the question, but some features of the whole model should be

evident, or not, within decades. Some examples include the magnitude-frequency distributions for the whole state, a subset of the state closely surrounding major faults, and the remaining subset. Another test is the fraction of all events above the lower magnitude threshold included in the on-fault category. Fault-specific tests include the fraction of times that earthquake ruptures stop within small regions where the UCERF model predicts frequent termination. Paleo-seismic data imply a rate at which sites should experience additional ruptures, observable within some decades. Retrospective tests of paleoseismic recurrence could also be informative. A new feature of UCERF3 includes the possibility of fault-to-fault jumps, testable over a longer period.

Challenges of Developing a Simulation-Based Risk Model: Are All Realization of Event Time Series Equally Relevant?

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The occurrence properties of ruptures, whether the long-term mean recurrence time or the time-dependent renewal properties, are assessed for ruptures or faults independently. Even in a Grand Inversion scheme, constraints on the order in which the ruptures occur are not present and the result, for the long-term average example, is given in terms of independent rates for each rupture of the ERF.

This is because what is characterized is the inter-event time distribution for each separate rupture.

Whether that distribution is chosen to be an exponential or a lognormal or another shape, it does not constrain the timing of events in the system, only the inter-event time distributions for each of the ruptures.

If these distributions are used to create time series of events in a system, this can lead to realizations in which there are periods of extremely large slip rates, in particular in regions where faults are subparallel (i.e., several faults can accommodate the relative plate motion), or on the contrary to 0, or very small slip rate if only the long inter-event times are sampled (relative plate motion on hold).

As the community goes towards simulation-based PSHA and risk models, this issue could become critical, even at the scale of a few years: the spread in the Exceedance Probability in hazard or losses from one realization to another could be huge, the cost to converge on the average properties for each fault as well, while the resulting medium-term (over a few large ruptures) fault slip rates might be deemed unacceptable by earthquake geologists. We propose examples of ways in which such slip rate constraints may be incorporated, both at the level of one fault and at the level of several faults.

Recent Advances and Findings in Earthquake Geology and Paleoseismology

Poster Session · Friday · 2 May · Cook/Arteaga

A Paleoseismic Transect of Forearc Lakes at the Latitude of Seattle, Washington

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We sampled lake sediments collected from forearc lakes along a transect from just west of the Olympic Peninsula to the Cascade foothills at the latitude of Seattle, Washington. Working with Brian Sherrod (USGS), we used a modified Livingstone corer deployed from a small floating platform. The lakes are (west to east) Beaver Lake, Leland Lake, Tarboo Lake, Hall Lake, and Lake Sawyer. These lakes are small (2–113 ha), range in depth from 6–17 m, and are all kettle lakes other than Beaver Lake (a landslide-dammed lake). The sediment cores are composed primarily of organic-rich gyttja and visually show little downcore variability, except for the presence of a thick tephra at about 6–7 m at many of the sites (other than at Tarboo Lake which has little overland flow and thus much lower clastic input). The tephra is likely from the eruption of Mt. Mazama based on its similar depth occurrence in previously published cores. Computed Tomography (CT) density, gamma density, and magnetic susceptibility data show there is much more variability in sediment composition than is visually apparent, which initial investigation suggests is in part a function of variations in the percentage of clastics as compared to organics. Preliminary correlations of the core data along this 185 km transect show strong similarities in density variability between these cores over the past ~7600 years when anchored by the Mazama tephra. We have also made preliminary comparisons with offshore cores and find that the downcore variability in physical properties match the offshore cores equally well. Given the evidence for earthquake origin for the offshore cores, and the strong common signal across the lake transect, we suggest that the density and magnetic susceptibility patterns in the lake transect are most like of earthquake origin, representing turbidites generated internally within each lake, and therefore represent the first cross-forearc paleoseismic transect in Cascadia.

3-D Investigation of Channel Morphology across the San Andreas Fault Zone using Structure from Motion and Terrestrial Laser Scanning

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The Carrizo section of the San Andreas fault (SAF) is an excellent location to study the interplay between earthquake offset and geomorphic evolution of stream channels. Fault-parallel trenches that cut across ephemeral surface channels reveal slices of buried offsets allowing for insights into the 3-D geometry of channel stratigraphy across a fault zone. In the Carrizo Plain, few researchers have explored how cut-and-fill sequences may indicate local paleotopography and past weather events as well as how channels respond to earthquakes and evolve during interseismic periods. Fault-parallel trenches were excavated on either side of the SAF at Phelan Creeks (230 m channel offset; ~3km SE of Wallace Creek) and Sieh31 (5–10 m channel offset; ~5km SE of Wallace Creek). Channel morphology at both sites was captured by trench logging, trench photography and balloon aerial photography as well as terrestrial laser scanning (TLS) of trench walls at Sieh31. All trenches show stratified alluvial fan units incised with distinct channel cut-and-fill sequences. The Phelan Creeks channels we excavated were abandoned several ka and show significant soil and colluvial development. Trench excavations revealed that the surface and buried channel margins and thalwegs are not stacked. The channel fill sequences are interpreted to result from the interplay of initial abrupt incision followed by episodic earthquake offset, channel cut-and-fill, steady biogenic and pedogenic shallow surface modification, and colluvial facies development. We present initial findings of the 3-D subsurface channel morphology over the SAF zone at Phelan Creeks and Sieh31 as indicators for the geomorphic evolution of cut-and-fill sequences and burial history in the Carrizo Plain. In addition, we discuss methods and workflow development for TLS and Structure from Motion (SfM) modeling for a planned progressive 3-D trenching project at Sieh31 which would accurately map subsurface channel geometry across the SAF.

Is There a Discrepancy Between Geological and Geodetic Slip Rates along the San Andreas Fault System?

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Several previous inversions for slip rate along the San Andreas Fault System (SAFS), based on elastic half-space models, show a significant discrepancy between the geological and geodetic slip rates along a few major fault segments. We use a more realistic model of an elastic plate over a viscoelastic mantle to demonstrate that there is no significant discrepancy between long-term geologic and geodetic slip rates. The model includes steady slip along 40 major fault segments from the base of the locked zone to the base of the elastic plate along with episodic shallow slip based on known ruptures. The slip rates are constrained by 1989 velocity vectors from EarthScope GPS and ALOS InSAR data. In addition to slip rates, our inversion solves for the translation and rotation motion, as well as shallow creep along several creeping faults.

The geodetic slip rates inferred from a model consisting of a 60 km thick plate and 1019 Pa s viscosity agree to within the bounds of the geological slip rates, while the rates from a simpler half-space model disagree on the Mojave and the North Coast segments. In particular, along the Mojave segment, the recovered geodetic slip rate is 24.7 mm/yr for the half-space model but the result comes closer to the preferred geological rate of 34 mm/yr using a 60 km thick plate model (27.5 mm/yr) and a 30 km thin plate model (34.4 mm/yr). The plate models have generally higher slip rates than the half-space model because most of the faults along the SAFS are late in the earthquake cycle, so today they are moving slower than the long-term cycle-averaged velocity as governed by the viscoelastic relaxation process.

We also explore the dependency of transient deformation on paleoseismology data (i.e., known ruptures extending back 1000 years). We found that the assumption

of the characteristic earthquake model plays a minor role on the inferred slip rates, but the timing of the major events has a greater influence on slip rate result.

Near-Field Post-Seismic Deformation of the 1992 Landers Earthquake using Time-Series Analysis of ERS and Envisat InSAR

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The 1992 Landers earthquake was the first event imaged by InSAR both over the coseismic and post-seismic period. The post-seismic displacement field showed (1) broad scale patterns interpreted as the combined effects of fault after-slip, poroelastic relaxation in the shallow crust, and viscoelastic relaxation in the deeper crust and upper mantle, (2) localized subsidence and uplift in fault step-overs interpreted as a poroelastic rebound in the stretched and compressed volume of rock near the fault, and (3) surface creep along certain sections of the fault. We reanalyze the near-field using full-resolution Envisat and ERS images. To understand the magnitude and temporal dependence of the surface deformation, we construct a time series of surface displacement of the near-field using the small baseline subset approach. We estimate the characteristic time of specific areas along and within the fault zone and discriminate between specific mechanical processes based on time-dependence.

Estimation of Coseismic Ground Deformation in the Mexicali Valley, Baja California, Mexico, during 2006–2009, using Precise Leveling, DInSAR and Geotechnical Instruments Data

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The Mexicali Valley, located in northeastern Baja California, Mexico, in the southern part of the San Andreas Fault system, is characterized by high seismicity. Sixteen earthquakes, in the 4.5- 5.8 magnitude range, occurred in the Mexicali Valley during 2006–2009, some of them causing moderate destruction, visible surface deformation and faults rupture. The goal of this study is to show whether using accessible geodetic and geotechnical data we are able to identify ground deformation related to these earthquakes.

The ground deformation in this area is caused not only by earthquakes and continuous tectonic deformation, but also by human activity; mainly by the geothermal fluid extraction in the Cerro Prieto Geothermal Field. Distinguishing deformation caused by human activity from that due to natural processes is essential for making informed assessments and mitigation of natural and anthropogenic hazards.

Here we use the results of ground deformation monitoring in the Mexicali Valley during 2006 to 2009. The precise leveling data span more than 3.5 years and contain both anthropogenic and natural deformation. Due to its large magnitude, the anthropogenic deformation component significantly obscures the possible tectonic signal. Differential Interferometric Synthetic Aperture Radar (DInSAR) imagery is used to estimate the deformation associated with geothermal fluid extraction occurred during this period. DInSAR stacking techniques were applied to SAR images captured in 2007 when there was no significant seismicity in the study area.

After removing the estimated non-tectonic signal from the leveling data, we are left with several anomalies. We analyzed continuous tilt and extension data from the geotechnical instruments network REDECVAM (Mexicali Valley Crustal Strain Measurement Array), in order to identify time occurrence of deformation signals and associate observed anomalies with deformation caused by moderate-sized earthquakes occurred in the area of study.

Reevaluation of the Pyramid Lake Fault Zone Slip Rate: Integrating High-Resolution Datasets from LiDAR, Drone Photography, and Aerial Photographs

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The application of high-resolution surface datasets to active tectonics has increased our ability to identify subtle tectonic signatures that may have otherwise been overlooked or remain unidentified, warranting reevaluation of faults where discrepancies and/or inconsistencies have surfaced. The Pyramid Lake fault zone (PLFZ) is a well-developed northwest trending right-lateral fault in the northern Walker Lane, located about 30 km east of Reno, NV. Previous paleoearthquake and slip rate studies indicate that the fault has produced 3 surface rupturing paleoearthquakes since 8980 +− 260 cal. Yr B.P. and has an average minimum slip rate of ~2.6 mm/yr. Reconciling these two observations, given that they are correct, requires that coseismic offset must have averaged ~7 to 9 meters, larger than would generally be expected from empirical scaling relationships for a strike-slip fault of its 45 km length. We are currently reevaluating and will measure geomorphic offsets along the PLFZ using multiple high-resolution surface datasets. Our specific intent is to reexamine previously identified offsets and search for evidence of repeated single-event offsets in the geomorphology. The approach being taken first utilizes scanned 1:10k black and white low-sun angle photographs to construct a large-scale digital elevation model (DEM) of the PLFZ. The DEM is then used to define areas that holds the most promise to record small geomorphic offsets. Terrestrial LiDAR and Drone photography are finally used to create high-resolution DEMs and contour maps of the respective sites.

Preliminary Paleoseismic Trenching Results from the Flat Canyon Site, Southern Provo Segment, Wasatch Fault Zone: Testing Holocene Fault-Segmentation at the Provo-Nephi Segment Boundary

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Paleoseismic data near fault segment boundaries provide direct information about fault rupture segmentation. The 350 km-long Wasatch fault zone (WFZ), the archetype of segmented normal faults, consists of 10 structural segments. Abundant paleoseismic data support a history of segmented Holocene surface ruptures, but recent findings document at least one case where an earthquake ruptured across a WFZ structural segment boundary. The extent and frequency of ruptures that span segment boundaries remains poorly known, in part because most paleoseismic studies are sited in segment interiors, adding uncertainty to seismic hazard models for this heavily populated region of Utah.

To address these unknowns and reduce this uncertainty we have begun a paleoseismic trenching campaign targeting WFZ structural segment boundaries. We excavated a trench at Flat Canyon (Salem, UT), near the southern end of the Provo segment in the complex Provo-Nephi segment boundary, a 5–8 km-wide right stepover. Alluvial fan deposits at the site are displaced across a 13 m-high scarp. We document a minimum of four and maximum of seven earthquakes within a 17–20 m-wide fault zone, consisting of two graben systems within the scarp. The lower graben preserves evidence for four earthquakes and ~5 m of vertical throw. The upper graben preserves evidence for two to three earthquakes with ~1 m of total throw. Ongoing optically stimulated luminescence and radiocarbon analyses will provide earthquake timing constraints and allow us to correlate earthquakes between the grabens.

Our goal is to determine whether earthquakes at the Flat Canyon site correspond with earthquakes at several paleoseismic sites farther north on the Provo segment and/or with earthquakes at the northernmost sites on the adjacent Nephi segment to the south. Comparison of these earthquake chronologies will allow us to test whether Holocene earthquakes have ruptured across the Provo-Nephi segment boundary.

Revised Earthquake Timing and Displacement Data Indicate Complex Fault-Rupture Behavior for the Central Wasatch Fault Zone, Utah

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The 350-km-long Wasatch fault zone (WFZ) forms the prominent eastern boundary of the actively extending Basin and Range Province of northern Utah and southern Idaho. The WFZ includes five central fault segments defined by structural and geometric boundaries (bedrock salient, fault step-overs, and significant along-strike changes in fault geometry) and distinct Holocene earthquake timing and displacement histories. Following an analysis of paleoseismic data for the central WFZ, we present a revised earthquake chronology comprising at least 22 surface-faulting earthquakes on the central segments in the past 6 kyr. Our revised earthquake times define unique earthquake chronologies for each segment, and thus support the concept of segmentation of the WFZ. However, we also found evidence of more complex fault rupture, including possible partial ruptures of the Salt Lake City segment and a spill-over rupture across the Weber–Brigham City segment boundary.

The revised chronology yields consistent mean recurrence intervals of ∼0.9–1.3 kyr per segment, but we also found aperiodicity in recurrence (a composite coefficient of variation on the WFZ is ∼0.5) that stems from several longer (∼1.9–2.5-kyr) inter-earthquake times per segment. A possible explanation for the aperiodicity is complex stress interaction among segments. Finally, vertical displacements per earthquake are large (mean of 2.1 m) and yield moment magnitude estimates from empirical relations that exceed those based on segment length. Although our revised chronologic and displacement data for the past 6 kyr support the current model of WFZ segmentation, examples of complex rupture processes (in space and time) in the paleoseismic record create uncertainties that should be accounted for in probabilistic seismic hazard analyses of the Wasatch Front region.

Evidence for Quaternary Reverse Slip of Rattlesnake Mountain Fault, Yakima Fold Belt, Eastern Washington

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Rattlesnake Mountain, which lies within the Yakima Fold Belt of eastern Washington, is part of a longer structure, the Rattlesnake Mountain–Wallula segment of the Rattlesnake Hills structure (RAW). Since detailed studies of this region were initiated in the late 1970s, controversy has existed regarding the style and rate of contemporary deformation on this system of faults. Previous mapping, which focused on structure and stratigraphy within the Miocene basalt units identified two steeply-dipping reverse faults along its steep northeastern slope and an anticline ∼1 km outboard of the range front (Reidel, in press). More recently, it has been postulated that streams originating in the range exhibit right-lateral deflections of up to 250 m, suggesting significant Quaternary strike-slip movement (Blakely et al 2013 in press). Desktop analysis of LiDAR data, field mapping, and dating of pedogenic carbonate using U-series analysis, conducted for the Hanford SSHAC Level 3 PSHA finds geologic evidence of reverse Quaternary faulting along both the main range front fault and on a blind fault underlying the outboard anticline. Although some component of oblique slip is possible, the lack of displaced fan heads or features, such as shutter ridges, argue against significant strike-slip movement. Of the three mapped late Pleistocene alluvial fans and one early to middle Pleistocene bajada surface, only the oldest bajada surface (Qaf 4) is demonstrably offset or deformed across both the range front fault and anticline. The age of Qaf 4, which is vertically displaced 20–30 m across the fault zone, is estimated to be middle Pleistocene ($>$ 400 ka to 1 Ma) yielding a Quaternary slip rate of $\sim$ 0.02–0.075 mm/yr. A long-term slip rate based on the structural relief of the Saddle Mountains basalt is similar (0.07–0.12 mm/yr). The timing of the most recent event is constrained by the estimated age (12–31 ka) of the oldest alluvial fan unit (Qaf 2) that clearly is not offset by the fault.

Recently Discovered Northeast-Oriented Transpression Structure in the Northern New Madrid Seismic Zone

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High-resolution seismic-reflection profiles acquired 12-km northeast of the New Madrid seismic zone's northwest-oriented Reelfoot left-stepover thrust and along the central axis of the Mississippi embayment imaged steeply dipping faults that have uplifted and arched post-Paleozoic sediments in a manner consistent with displacement having a significant dextral strike-slip component. The sub-parallel fault strands have been locally correlated between profiles. The structure extends over a 1.4 km distance and strikes N 30° E. In an initial attempt to evaluate the structure's potential regional scale, the strike was projected northeast 22 km to its intersection with the nearest existing seismic image. This lower-resolution industry reflection profile exhibited a 0.75-km-wide structure with similar style and architecture at the intersection. The high-resolution images indicate the deformation extends above the Paleozoic bedrock, affecting Cretaceous and Eocene sediment, as well as crossing the base of the Quaternary. The Paleozoic and Cretaceous horizons show as much as 75 and 50 meters of relief, respectively, with the middle Eocene and basal Quaternary disrupted 25 and 15 meters, respectively. Geologic and geophysical logs from an adjacent borehole constrain the depth, velocity, and stratigraphic interpretations for the high-resolution data set. The faults, orthogonal to the Reelfoot stepover, are also too far inboard to be part of the rift boundaries; these preliminary data indicate the structure may be related to an extension of the northeast-oriented southern shear zone across the stepover.

Rupture Properties of the Mw 7.7 2012 Haida Gwaii Earthquake from an Empirical Green's Function Method

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This study examines rupture properties of the October 28, 2012, M_w 7.7 Haida Gwaii earthquake off the coast of British Columbia using an empirical Green's function (EGF) technique. Surface waveforms from a 2001 M_w 6.3 event, which ruptured only 15 km from the 2012 epicenter with an almost identical mechanism, are used as an EGF to be deconvolved from those of the 2012 mainshock. The resulting source-time function is free of path effects and instrument response, so the waveform displays only properties of the rupture itself. By examining azimuthal variations in these source-time functions we can constrain parameters such as average rupture velocity, rupture extent, and directivity. Additionally, information can be gathered about the possible existence of major sub-events and their locations. Preliminary results indicate that the overall rupture extends to the northwest for approximately 135–170 km along a direction similar to the strike (∼320°). These findings are important, given that earthquakes with strong directivity, such as the 2002 M_w 7.9 Denali earthquake, have been shown to be capable of triggering earthquakes thousands of kilometers away. One important question to be addressed is whether there is a link between the Haida Gwaii event and the M_w 7.5 earthquake at Craig, Alaska (350 km northwest), just two months later.

The Haida Gwaii earthquake was the largest event along the Canadian portion of the Pacific – North America plate boundary since the M_s 8.1 Queen Charlotte earthquake of 1949. Focal mechanisms in this region are predominantly right-lateral strike-slip but with an element of oblique convergence off Moresby Island. This work aims to elucidate important information about the rupture process, which is thought to have involved a blind thrust fault dipping gently to the NE rather than the main, sub-vertical Queen Charlotte Fault.

The 2010 Salta Earthquake. Focal Mechanism, Slip Distribution and Seismogenic Source from Seismic and Insar Data

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The Salta earthquake of February 27, 2010 was the first M6 shallow event recorded in the Lerma valley (where almost one million people live) since the begining of the instrumental registration. Both sinistral transcurrent and reverse with sinistral component focal mechanisms have been proposed (Alvarado et al. 2011; García et al. 2011). Using the location and the spatial distribution of aftershocks published by Sanchez Girino (2012), we re-calculate the focal mechanism and estimate the size of the rupture, respectively. The tensor obtained by teleseismic body-wave inversion (Kikuchi and Kanamori 2003) is mainly compresive with a small sinistral component and the solution planes are P1:335/63/86 and P2:164/27/99 at a depth of 14 km. Given the P1 solution and a rupture lenght of 21 km along the strike, we model the slip distribution following the method of Hartzell and Heaton (1983). The distribution shows the higher slip values concentrated at 10 km depth and 15 km to the WNW from the hipocenter. The best-fit tensor obtained from InSAR data (Scott et al. 2012) is very similar to the described above. We jointly inverted six interferograms for the slip distribution fixing strike, dip and rake to the values from the P1 solution. The obtained location of the slip centroid is −24.8526, −65.7656 at a depth of 9.6 km. The geometry of the P1 solution and the location of the slip centroid allow us to propose the El Gólgota fault as the seismogenic source for the 2010 Salta earthquake. This structure is a west-verging 80 km-long reverse fault that thrusts Proterozoic-Early Cambrian basement rocks over Cretaceous and Cenozoic sediments. The Quaternary activity of this fault has been previously reported by Marrett et al. (1994). Recent studies (García et al. 2013) have reported Late Quaternary deformation in the Lerma valley, showing the relevance of neotectonic and paleoseismological studies to asses the seismic hazard in this region.

Factors Contributing to Multi-Segment Rupture in the 2010 M7.1 Darfield, New Zealand, Earthquake

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We use dynamic prescribed slip (kinematic) and spontaneous rupture modeling to examine the factors contributing to multi-segment rupture in the 2010 M7.1 Darfield, New Zealand, earthquake. We consider fault geometry and slip distributions from inversions by Beavan et al. (2012) based on geodetic observations and Elliott et al. (2012) based on geodetic and teleseismic observations. We find that dynamic stress changes, as well as the the orientation of the faults with respect to the regional stress field and the compressional strain regime, create favorable conditions

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for triggering of the main rupture on the Greendale fault from rupture initiating on the Charing Cross fault. The Charing Cross fault is a small reverse fault that is compatible with both regional first-motion focal mechanisms as well as inversion of regional data for an initial moment tensor solution. The relative orientation of the regional stress field and the faulting regime may have also contributed to triggering rupture on a few other small faults on which the finite-fault inversions image minor slip. Owing to their complexity, recorded waveforms provide relatively poor constraints on whether coseismic slip and dynamic triggering occurred on some of the faults with much less slip. Current work focuses on evaluating how well the UCERF3 (USGS Open File Report 2013–1165) criteria for forecasting multi-segment ruptures in California apply to this complex rupture in New Zealand.

Paleoseismic Investigations of the Kango fault, South Africa: Incorporating Temporal and Spatial Clustering Behavior into a Seismic Source Characterization Model

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The Kango fault (a Mesozoic basin-bounding fault) lies in a seismically quiescent region within the Eastern Cape Province of South Africa, but has evidence for three latest Pleistocene to Holocene surface-faulting events preceded by a long period of several tens of thousands of years of no activity—behavior typical of other stable continental region (SCR) faults. The 92–101 km long eastern segment of the Kango fault appears to be unique among the faults within the Ceres-Kango-Baviaanskloof-Coega fault system in that it shows evidence of repeated normal-slip surface-rupturing events in the Quaternary. The occurrence of these events—two events in the past 10–15 kyr along the western part of the approximately 100 km–long reactivated portion of the fault, and at least one event between 22.6 ka and 25.4 ka along the eastern part of the reactivated part of the fault—indicates that the Kango fault may be within a period of higher activity. Low cumulative Quaternary displacements (10–33 m) and low long-term average slip rates are based on measured offsets of high pediment surfaces and a buried erosional strath surfaces that record long-term (350 kyr to 3 Myr) deformation rates on the reactivated part of the Kango fault. Paleoseismic trenching, geochronology investigations using both cosmogenic nuclide (10Be/26Al) and OSL dating methods, geomorphic mapping and analysis, drilling, and geophysical studies provide information on the size and timing of Quaternary faulting events. The results of these studies were incorporated into a seismic source model that accounts for temporal and spatial clustering in the assessment of the recurrence behaviour of the reactivated Kango fault and adjacent faults within the Ceres-Kango-Baviaanskloof-Coega fault system.

Comprehensive Study on Holocene Paleoearthquakes in Daqingshan Piedmont Fault, Inner Mongolia of China

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Daqingshan piedmont fault is a normal dip-slip fault. It spreads along south piedmont of Daqingshan in Inner Mongolia of China. This fault happened many frequent great paleoearthquakes in Holocene. Paleoseismic events of this fault since Holocene were revealed through digging and trench techniques. This paper studies Holocene paleosols on the paleo-alluvial-pluvial fans of hanging wall and gullies geomorphology of footwall which record the fault activity history.

On the hanging wall we study alluvial fans' sections containing the ancient soil layers at intervals. The results show that Daqingshan piedmont alluvial fans in Holocene develop 3 periods ancient soil layers. We assume that in the same period of soil development, the development of paleosol formation was interrupted and formed in similar time multiple interbeds of paleosol and gravel layers, which are caused by the fault activities. That is, the gravel layer between two adjacent paleosol layers represents an ancient earthquake event. Thus we can date paleosol layers which are up and down the gravel layer to define paleoseismic events.

On the footwall we extract gullies from high resolution IRS-P5 DEM data. 25 gullies across the fault on the footwall have been extracted from DEM. Knickpoints caused by fault activities in Holocene have been extracted from profiles of gullies for further step. Combining with the retreat distances and the retreat rates of knickpoints on the gullies, we get forming time of each rank knickpoints on the the fault. Thus, paleo-earthquake series in Holocene of the fault have been obtained.

We get Holocene paleoearthquakes records from both walls of the faults. Then we contrastively analyse the results with trenches results together. The result demonstrates that paleosols ages on the Paleo-alluvial-pluvial fans and knick points sequence on the footwall have very close correspondence relations with paleoseismic events along the Daqingshan piedmont fault.

Faulting Constraints and Incision Rates in the Krsko Basin and Upper Sava River, Eastern Slovenia

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Quaternary Incision rates have been constrained for the upper Sava River (roughly 100 km from the Alps) using cosmogenic radionuclide (CRN) burial 26Al/10Be dating, as well as quartz and feldspar optically stimulated luminescence (OSL). These new data have helped to constrain the ages of not only incision rates, but also tectonic features and processes in southeastern Slovenia, an area located within the transition zone between the Sava Folds and the southeastern extension of the Mid-Hungarian Zone and an area of low to moderate tectonic activity. Within the region, the geomorphic expressions of Quaternary tectonics and mass wasting processes are subtle due to heavy vegetation, anthropogenic activity, and reasonably high rates of erosion. Nevertheless, new topographic data from light detection and ranging (LiDAR) DEMs have allowed us to recognize and differentiate complex surface process – the coupling between tectonic and mass wasting processes that were previously identified as purely tectonic landforms.

The new CRN and OSL-derived geochronology has confirmed prior age estimates that were based on stratigraphic positions and limited geochronology. This confirmation is not surprising, although it is critical because recent conjecture has implied the region is far more tectonically active than previously believed. The geochronology from this study suggests that the region has been undergoing lower tectonic deformation rates than originally postulated. The LiDAR data have also shed light on the mass-wasting surface processes that have influenced the tectonic interpretation of the landscape. These data contribute to providing constraints on the ages of the Quaternary stratigraphy, ultimately providing constraints on regional deformation patterns. This has important implications for seismic hazard analyses for critical facilities and provides important insights as to the process-dominance between regional tectonics and climate as major agents of landscape change.

Seismic Location and Processing Techniques

Poster Session · Friday · 2 May · Cook/Arteaga

A Linear Formulation for Earthquake Location in a Homogeneous Half-Space Based on the Bancroft Algorithm Developed for GPS Location

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The traditional approach to both earthquake and GPS location problems in a homogeneous half-space result in a seemingly nonlinear relationship between a set of known positions, seismic stations or GPS satellites, and an unknown point, an earthquake hypocenter or GPS receiver. Linearization, followed by an iterative inversion, is typically used to solve both problems. Although sources and receivers are inverted in the earthquake and GPS location problems, the observation equation is the same for both due to the principle of reciprocity. Consequently, single step linear solutions for the GPS location problem, such as the Bancroft algorithm, can also be used to solve for earthquake hypocenters. We apply the Bancroft algorithm to synthetic data for the New Madrid seismic network, showing improvements in both precision and accuracy compared to traditional methods. We also show how tools commonly used by the GPS community can be used to better estimate the precision of locations obtained by a seismic network.

Low-Frequency-Earthquake Locations Determined using Time-Reverse-Imaging

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The low-frequency-earthquakes (LFEs) associated with non-volcanic tremor typically exhibit non-impulsive phase arrivals that inhibit the use of standard ray-tracing location methods. Here we use time-reverse-imaging techniques that do not require phase arrival identification to locate individual LFEs within tremor episodes on the San Andreas fault near Cholame, California.

We propagate a time reversed seismic signal back through the subsurface using a staggered-grid finite-difference code. We then search for wave field coherence in time and space (e.g. LFE energy in 1.5 second time windows filtered between 1–5 Hz) to obtain the source location and origin time where the constructive interference of the curl field energy is maximum. The grid point and time window occupying the spatial median of cross-correlation values within 10% of the maximum value indicate the source location and origin time.

Location errors are based on the spatial extent of all cross-correlation coefficient values exceeding 90% of the maximum value. Horizontal and vertical errors are on the order of 4 km and 3 km respectively. We check the locations determined here with an LFE catalog determined by stacking hundreds of LFEs [Shelly and Hardebeck, 2010]. The LFE catalog uses stacks of at least several hundred templates to identify phase arrivals to estimate the location. We find that the epicentral locations determined here using the time-reverse-imaging technique are within ~4 km of the catalog LFE locations [Shelly and Hardebeck, 2010]. LFEs locate at depths between 15–25 km, similar focal depths to previously published locations of LFEs or tremor in the region. Overall, the method can provide robust locations of individual LFEs without identifying and stacking hundreds of LFE templates, and is more accurate than envelope location methods with errors on the order of tens of km [Horstmann et al., 2013]. Location errors may be further reduced with increased velocity model resolution.

Preconditioning Seismic Data using the Hilbert Huang Transform Prior to Gradiometric Analysis

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A recorded seismic signal is typically a superposition of several disparate wavefields. This poses a challenge for any seismic array data analysis method that assumes only a single wavefield is recorded by an array at any given time. For example, the new method of seismic gradiometry is extremely sensitive to the violations of the single wavefield assumption. As a result, gradiometry returns unreliable results when applied to a signal that contains several superposed wavefields. In such a case, preconditioning the data using some form of wavefield separation method prior to gradiometric analysis can be helpful if the data contains wavefields with distinct time or frequency components.

However, most methods assume that the signal is stationary and linear. Given that seismic signals are neither stationary nor linear, it may be more helpful to employ a wavefield separation method that does not assume either. The Hilbert-Huang Transform (HHT) is an algorithm designed to decompose a signal which can contain nonstationary and nonlinear components. In this work, we explore the feasibility of applying the HHT to decompose the signal prior to gradiometric analysis.

Accurate Depth Determination of Earthquakes along the Kuril Islands Outer Rise from Waveform Modeling

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We will present our results of waveform modeling of teleseismic P-waves, based on an application of a 3D finite difference method, for the purpose of determining improved locations of earthquakes located in the outer rise area near the Kuril Islands. A series of large outer rise events occurred in the region of the Kuril Islands between 2006–2009. The depth and timing of these outer rise compressional and tensional earthquakes may provide important insight into the coupling of the subduction zone. Prior to a large interface event, tensional earthquakes generally occur at shallower depths, while compressional events occur at greater depths. Tensional events can also occur after an interface event at greater depths; whereas compressional events typically become non-existent after large interface events, reflecting the change in stress in the outer rise area. However, the hypocentral depths of outer rise earthquakes are usually poorly constrained, and often held fixed at 10–15 km depth in centroid moment tensor inversions. Outer rise events also tend to produce complex waveforms with large azimuthal variation due to the complicated velocity structure close to the trench and the interaction of the depth phases with this structure, the ocean bottom and water layer. The numerous earthquakes in this outer rise sequence, located in close proximity of each other, but diverse in terms of source mechanism, depth and horizontal location relative to the trench, offer a unique opportunity in the study of the importance of the incorporation of 3D subduction zone structure on depth phases. We will show the results of a comparison of 1-D and 3-D synthetics with teleseismic P-wave data for tens of tensional and compressional earthquakes.

Looking for Non Volcanic Tremor in Mexicali Valley, Baja California, Mexico

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The presence of Non Volcanic Tremors (NVT) was identified for the first time in the Japan subduction zones in 2002 (Obara, 2002). Because of its close association with geodetically observed slow-slip events and low frequency earthquakes in subduction zones, it was named Episodic Tremor and Slip (ETS). Nadeau and Dolenc (2005) detected tremor in Central California under the San Andreas Fault near Parkfield.

NVT triggered by surface waves has been observed many times in subduction zones (Beroza and Ide, 2011). NVT has also been observed in the San Andreas and San Jacinto faults triggered by the 2002 Denali earthquake, and in Taiwan triggered by the 2001 Kunlun earthquake (Peng et al., 2008, Peng and Chao, 2008, Chao et al., 2012).

A seismic sequence and deformation were triggered by the Hector Mine, M 7.1, 1999, earthquake (HME), and signals similar to NVT were observed at a broadband instrument installed in Mexicali Valley, Baja California, Mexico, 250 km from the epicenter (Glowacka et al., 2002).

A continuous seismic signal was recorded in Mexicali Valley in one instrument only and only during a few months in1999, and 2002–2005. We analyzed tremor-like signals triggered by the HME and Denali (M=7.2, 2002) earthquakes using the Kao (Kao et al., 2007) and Husker methods, (Husker et al., 2010). Signal characteristics obtained from the analysis are similar to NVT as noticed by Kao, but the fact that the analysis was made only for one instrument does not allow to conclude that what was recorded was in fact tremor, and where the source of the tremor is.

Also the presence of noise related to the fluid extraction and injection in the Cerro Prieto geothermal field and very noisy agricultural activity in Mexicali Valley do not help to identify seismic signals.

A more dense seismic network is necessary in order to carry out complete seismic studies in the tectonic and anthropogenic conditions of Mexicali Valley.

Scaling Rotational Motion and its Induces Effects

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A strong-motion accelerograph is designed mainly for measuring three-component translational accelerations. However, accelerometer can also detect rotation motions and related effects such as the centrifugal acceleration, gravity (ground tilt) effect and effects of rotation frame. Analyses of six-component ground motions (three-component translational motions and three-component rotational motions) can recover the translation motion and extract the rotational effects. Unlike the translational motion, the peak values of rotation motion and its effects are controlled by PGA rather than by the size and distance of earthquakes. We analyze a set of collocated and well recorded rotation rate-strong motion velocity data. Results show that the peak values of rotational effects vs. PGA are shown to be in quadratic form on a log-log scale which implies that these effects grow up very quickly in large ground motions. This relationship also implies that the rotational motions might have large variation at large translational motions. Both these features seem to fit the observations of near-field and extreme large ground motions.

Depths of Indian Ocean Intraplate Earthquakes From Waveform Modeling

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The Indian Ocean is a region of complex tectonics and anomalous seismicity. The great magnitude 8+ strike-slip events that took place in the Indian Ocean on April

11th, 2012 are unique because their rupture extended to a depth within the plate where seismic activity was considered to be impossible. The oceanic lithosphere in this region possesses many bathymetric features, most notably the multiple inactive fracture zones within the Wharton Basin, and the Ninetyeast Ridge. Studies have described the high seismic activity within the oceanic lithosphere in this area as delineating a diffuse deformation region where the Indian sub-plate is separating from the Australian sub-plate. Other studies have found that the aforementioned fracture zones have been reactivated due to the current stress regime.

We will present the results of our investigation of the focal depth of dozens of intraplate earthquakes that have occurred throughout the Indian Ocean in the past three decades. For these events, global moment tensor inversions are commonly carried out with fixed hypocentral depths, and a more detailed examination of the waveforms is required to determine accurate depths. A majority of the earthquakes we selected are between M5.5–6.5 with large tension axis plunge, chosen to provide optimal teleseismic P-waves for waveform analysis. 1D synthetic seismograms are computed for a range of depths based on existing lithospheric velocity models. Through a comparison of these synthetic waveforms with the recorded data we determine improved earthquake hypocentral depths

Examination of the Storfjorden Aftershock Sequence

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The Storfjorden aftershock sequence was triggered by a M_W 6.2 earthquake that occurred off the Spitsbergen's southeastern coast on February 21, 2008. Since its initiation, the sequence has generated thousands of aftershocks; several have exceeded M_W 4.0. Recent seismotectonic investigations have suggested the source of the sequence is not related to the nearby Billefjorden fault zone. Instead, its source is most likely tied to a NE-SW trending Tertiary shear zone. This conclusion is supported by the orientation of the relative relocations and the orientations of focal mechanisms for numerous sequence events [Pirli et al., 2013; Junek et al., 2014]. The results shown in previous studies [Pirli et al., 2013; Junek et al., 2014] were largely based on the analysis of manually reviewed events. However, the number of events in the NORSAR analyst reviewed bulletin represents a small fraction of the total number of events produced by the sequence. Here, an autonomous event detection and clustering framework is used to expand the available dataset. The expanded dataset is used to infer additional information about the tectonic structure within the fjord and to examine the sequence's spatiotemporal properties. The relative relocation catalog orientation and mixture of strike-slip and normal focal mechanism suggests the fault has a SW-NE trending en echelon structure.

Estimation of Rocking and Torsion Associated with Rayleigh and Love Waves, respectively, Identified on Recorded Motions

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We have proposed a new technique for the identification and extraction of Rayleigh and Love waves on earthquake motion traces. The above technique is based on the use of the Stockwell Transform (S-Transform) which provides the tool for the time-frequency (TF) analysis of non-stationary (and in particular dispersive) signals.

Making use of the capability of identifying and extracting the surface waves of a seismic signal, we can proceed to estimate the angular displacement (rotation about the horizontal axis normal to the direction of propagation of the wave; rocking) associated with Rayleigh waves and the angular displacement (rotation about the vertical axis; torsion) associated with Love waves.

If the wave (e.g. Rayleigh) were a simple harmonic wave, rocking would be proportional to the vertical velocity (harmonic) component and inversely proportional to the phase velocity corresponding to the particular frequency of the harmonic wave (as originally suggested by Newmark). Evidently, a reliable estimate of the phase velocity (as a function of frequency) is necessary. As pointed out by Stockwell, because of its absolutely referenced phase information, the S-Transform can be employed in a cross spectrum analysis in a local manner. Following this suggestion an estimate of the phase velocity may be obtained from two nearby stations. Synthesis of the abovementioned harmonic components can provide a reliable estimate of the rocking motion induced by an (extracted) Rayleigh wave. An analogous argument can be proposed to estimate the torsion induced by a Love wave.

We apply the above approach to estimate the rotational strains for various cases of well recorded data of basin-induced surface waves (including the case of the Western Coastal Plain, Taiwan).

A Pure-Python Phase Picker and Event Associator

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We developed a robust method for automatic phase arrival and event association applicable to real-time monitoring or archived data processing. This system consists of two main components FBpicker and Associator. These two modules could work separately or jointly depending on users' requirements, providing users flexibility to process data in term of their own priorities. Our system uses the statistical concept of characteristic function from Lomax et al. (2012) and in Python. The algorithm takes advantage of existing seismological and scientific Python libraries such as ObsPy (Beyreuther et al., 2010). The system is designed to work on a variety of instrumentation automatically adapting to different sampling rates and instrument gains. The time series signals are octave filtered for each band. We take band-pass filtered energy as characteristic function to detect changes of energy at phase onset. By simply taking the maximum statistics of all bands of each sample, we summarize the statistics. We trigger potential picks with a dynamic threshold based on the summary statistics. This has the advantage that the picker does not have channel specific configurations when processing data from a wide variety of instrumentation with different response characteristics. The algorithm also contains a method to determine the first motion direction associated with a pick. As with any automatic phase identification system false picks can and do occur. A few simple algorithms are implemented to avoid false-picks, and are highly configurable. These algorithms remove picks that occur very close in time and picks for which a phase has a smaller signal immediately after the pick than preceding the pick. The algorithm also uses techniques within Numpy to improve computation efficiency. Moreover, we implemented an Associator to associate the picks from FBpicker to events and assign phases.

Revised Geometry of Nodal-Plane Uncertainty Volume Used in the Seismo-Lineament Analysis Method to Locate Seismogenic Faults

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At the core of the seismo-lineament analysis method (SLAM; Cronin et al., 2008, *Env & Eng Geol* 14(3), 199–219) is a procedure for defining the intersection between the ground surface and the uncertainty volume associated with each nodal plane derived from an earthquake focal mechanism solution. This intersection is called a *seismo-lineament*. Given a sufficiently accurate focal mechanism for a well-located earthquake on a fault that is emergent and approximately planar, the ground-surface trace of the fault that generated the earthquake is likely to be located within the seismo-lineament swath. We have developed the solution for the quantitative description of the nodal-plane uncertainty volume given the uncertainty in nodal plane orientation and the triaxial uncertainty ellipsoid around the hypocenter.

In an emergency response context after a major earthquake, the revised SLAM procedure can help identify where ground-surface rupture might have occurred. This procedure is also useful for spatially correlating historic earthquakes with the faults that produced them, and as a reconnaissance tool in the search for seismogenic faults that might not have been recognized in areas where fieldwork is difficult because of logistics, vegetation, water/snow/ice cover, high relief, or access restrictions. The shape of the seismo-lineament defined by the revised SLAM procedure resembles a bow tie, with a relatively narrow area near the epicenter broadening away from the epicenter along nodal-plane strike. The SLAM procedure has been implemented in code written in *Mathematica* that defines the boundaries of a seismo-lineament on a DEM-based hillshade basemap. A manual method is under development that uses a spreadsheet or calculator and a conventional topographic map of the epicentral area.

Predicting P and S Wave Body Wave Travel Times at Regional and Teleseismic Distances

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We recently constructed a global-scale P-wave model (LLNL-G3D version 3, Simmons et al. 2012, JGR) designed to predict travel times for the first arriving P-wave energy at regional and teleseismic distances (Pn and P phases). The model is complex with undulating structures explicitly represented including 7 crustal

units, the Moho, and the upper mantle phase transitions. The explicit aspherical representation of the Earth is required to perform true 3-D ray tracing, which was employed to construct the model. Our tests have demonstrated a significant improvement in event location accuracy using P and Pn travel times predicted from the LLNL-G3D model. There is a need to predict additional seismic phases using a single model so that the travel times are self-consistent. Therefore, we have developed full 3-D ray tracing procedures for additional seismic phases (pP, PcP, PKP branches, PP, Pb, PmP, Pg, and numerous S-wave phases). We have constructed the next version of the LLNL-G3D model which is a simultaneous inversion of P and S wave heterogeneity linked together through relative heterogeneity ratios. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Tracking Fluid Movement in Volcanic Systems

Poster Session · Friday · 2 May · Cook/Arteaga

Calibration of the Seismic Network at the Hawaiian Volcano Observatory: Improvements to Locations and Magnitudes

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Using monies from the American Recovery and Reinvestment Act (ARRA), the seismic network at the Hawaiian Volcano Observatory (HVO) was fully upgraded to digital telemetry, with many instrumental upgrades and several new stations installed. The increase in dynamic range of the network and additional stations requires a recalculation of the station delays and magnitude corrections to enable improved location and magnitude solutions. We take this opportunity to subdivide Hawaii into subregions and assign new velocity models to these regions based on published studies. These velocity models also use a fixed datum (sea level). With Mauna Loa and Mauna Kea reaching over 4 km above sea level it is important to have a fixed datum from which to calculate earthquake depths and construct more physically realistic models of magma transport. The resulting locations with updated velocity models and delays have improved RMS misfits.

The network upgrades also requires an update to the existing calibration and station corrections of local magnitudes (M_L) and duration magnitude (M_d). An updated calibration and correction for the network will allow a more consistent measure of magnitude, particularly at small magnitudes where volcanic earthquakes are most numerous. The calibration of local magnitude follows the procedure of Bakun and Joyner (1984). The duration magnitude is tied to the local magnitude and station corrections are calculated accordingly.

More accurate estimates of both location and magnitude afforded by updated location and magnitude corrections will assist in more accurate future assessments of volcanic hazard.

Mapping Magma Pathways with Tremor at Kilauea Volcano

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Three distinct tremor source regions have been identified at Kilauea volcano. At depth, intermittent tremor and earthquakes occur in the Southwest Rift Zone (SRZ) approximately 40 km below and 40 km SW of the summit. In the East Rift Zone, tremor is recorded near Pu*ú*Ó*ó*, a vent that has been active since 1983. At the summit, nearly continuous tremor is recorded close to a persistently degassing lava lake. Local seismicity correlates with spattering at the lake surface, but summit tremor also occurs in the absence of spattering and was observed prior to the appearance of the lava lake in 2008 in association with inflation/deflation events. The continuous and emergent nature of tremor precludes the use of traditional seismic methods for routinely detecting and locating such seismicity, but tracking these signals is fundamental for elucidating magma transport dynamics. We implement an automated envelope cross-correlation method [Wech and Creager, 2008] to both detect and localize seismic tremor in the three regions by maximizing signal coherency among seismic stations in every 5-minute window. This approach has relatively poor depth constraints due to the construction of the envelope function; nevertheless, the epicenters distinguish activity among the different source regions and serve as starting points for more sophisticated location techniques. We apply this method in real time, building on a tremor catalog beginning January 1, 2013 that quantifies tremor rates and maps out each source area. Preliminary results identify a zone of tremor activity between the 40-km deep SRZ and the summit, suggesting magma source continuity from depth to the caldera. Regional tremor rates are not correlated, but extending the analysis to past data may reveal temporal relationships among the sources. With this systematic and real-time approach, we map magma geometry and quantify background behavior for each source to better understand, monitor and forecast Kilauea activity.

Seismic Structure of the Tonga Arc and Lau Backarc Spreading Center from Local and Teleseismic Body Wave Tomography

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The Lau Backarc Spreading Center and Tonga Arc provide an excellent environment in which to apply mantle seismic imaging to the study the dynamics of magma production and migration. The Central Lau Spreading Center, Eastern Lau Spreading Center, and the Valu Fa Spreading Center show very different characteristics as a function of their distance to the arc and slab, which decreases from north to south. Geochemical studies also indicate a systematic change in magma composition along strike of the Lau Back-Arc Spreading Center with more water and fluid-mobile elements in the south. From 2009–2010, 16 broadband seismometers and 51 ocean bottom seismometers (OBS) were installed for one year across the Lau backarc spreading centers and in Fiji and Tonga to image the along-strike structural variation of the subduction zone and the dynamics of the melt production region. OBS performance was excellent and all OBSs except one were recovered, with a $\sim$ 90% data return. We present preliminary results from the joint inversion of P and S wave arrivals from local and teleseismic events as recorded by this temporary network. Arrivals from local events are picked manually, while travel time residuals for teleseismic arrivals are determined via the adaptive stacking method developed by Rawlinson and Kennett (2004). A preliminary set of travel times for local events and residuals for teleseismic events are inverted using TOMOG3D (Zhao et al., 1994) to solve for three dimensional velocity structure along strike of the Lau Backarc Spreading Center and Tonga Arc.

Deep Seismicity Linked to Shallow Unrest at Little Sitkin Volcano, Alaska

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A swarm of shallow ($<$ 10 km depth) volcano-tectonic (VT) earthquakes beneath Little Sitkin Volcano began on August 29, 2012 and continued intermittently through November 2012. InSAR imagery indicates that 1–2 cm of inflation occurred beneath the summit between September 2012 and August 2013, suggesting that the seismic activity was related to an intrusion of magma below the edifice. Magma intrusions deduced from the combined InSAR imaging and seismic analysis have been observed at several volcanoes in Alaska, such as the 1996 swarm at Akutan.

In the days prior to the beginning of the swarm, a sequence of 5 unusual low frequency earthquakes occurred at Little Sitkin followed by a deep ($\sim$20 km depth) VT earthquake. One event occurred on August 23, another on August 24, and three in close succession on August 25. The deep VT occurred two days later, on August 27. We have dubbed the low frequency earthquakes bass tornillos (BTs) and refer to them here as BTs. The BTs had 2 distinctive, unusual characteristics: their signals were dominated by a single spectral peak at $\sim$0.57 Hz; and they were clearly observed up to a range of 80 km on seismometers located at Amchitka Island and Semisopochnoi Volcano. The first BT had impulsive P- and S- arrivals on the three-component broadband at Amchitka.

Although the BTs cannot be located by standard techniques, their low frequency content allows beamforming on a tripartite array comprised of the 3 local stations at Little Sitkin. Beamforming shows the apparent velocity of the BTs gradually decreased from 10 km/s to 5 km/s over the 60 s duration of their signal; however, backazimuth toward the southwest remained constant. These results suggest that the BTs occurred at depths greater than 15 km in relative proximity to the subsequent deep VT earthquake. The dynamics of the BT source evolved from radiating predominantly P-waves to S-waves over the course of the event, which explains the gradual decrease in apparent velocity.

Lower-Crustal and Upper-Mantle Seismicity Beneath Aleutian Arc Volcanoes

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Since 1989 the Alaska Volcano Observatory has identified more than 3,000 seismic events at upper-mantle to mid-crustal depths beneath 33 active Aleutian arc

volcanic centers. All Aleutian arc volcanoes with suitable instrumentation and long-term monitoring exhibit some amount of mid-crustal to upper-mantle seismicity. Epicenters typically scatter broadly around the volcanoes at distances up to 25 km from the closest volcanic vent. Depths for these events usually range from 15 to 45 km below sea level and magnitudes of located events range from −0.25 to 2.9. These events provide some of the only direct geophysical evidence of magmatic processes in the lower-crust and upper-mantle, a portion of the magma pathway that is traditionally difficult to observe.

The waveforms of these events contain frequencies from 1 to 15 Hz and are similar to event typically seen in volcanic environments from broad spectrum (1 to 15 Hz) brittle failure, volcano-tectonic earthquakes, to peaked spectra (1 to 4 Hz), fluid resonance or long-period events. To characterize the frequency content of these events consistently we have calculated the peak frequency of the observed waveforms using a 20.48 second portion of the waveform beginning at the onset of the P-wave arrival. Waveform cross correlation analysis indicates that over 100 event families have been recorded in the 15 to 45 km depth range using a minimum cross-correlation coefficient of 0.75. The percentage of repeating events to overall seismicity varied from 35% to 0% at different volcanic centers.

Joint Inversion of Ground Rotation and Translation from Small Explosions at Fuego Volcano

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Very-long-period events (12 s − 120 s) accompany explosive eruptions at many volcanoes and have been used to investigate conduit geometries and explosion source processes. At some volcanoes, a measurable rotation signal accompanies the VLP and can be recorded with seismometers. The horizontal components of broadband sensors are particularly sensitive to tilt, which may dominate the record at periods below the low corner of the sensor. Since tilt typically influences only frequencies much lower than the displacement signal, it can be filtered out prior to inversion; yet the tilt data can provide additional constraint on the source process and could be a valuable addition to the inversion.

At Fuego volcano in Guatemala, we recorded dozens of small-scale explosions in 2009 and 2012 using temporary arrays of seismometers and complementary instruments. These events are frequently preceded by 5 to 20 minutes of tilt that suggest pressurization of the upper conduit. The onset of explosive eruptions, which last from many tens of seconds to more than two minutes, include VLPs with peak periods from less than 30 to nearly 50 seconds. The events are dominated by ash emission that suggests a vulcanian-style downward migration of the magma fragmentation front.

Joint inversions of the seismic and tilt signals – as recorded by seismometers – using separately-derived synthetic tilt and displacement Green functions provides a more complete view of the eruption process at Fuego. Importantly, because the tilt begins prior to the explosions this modeling can provide better constraint on the pre-eruption process which may lead to more accurate eruption forecasting.

Conduit Processes Driving Pre-Explosive Harmonic Tremor in the 2009 Redoubt Volcano Eruption

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During the 2009 eruption of Redoubt Volcano, Alaska, gliding harmonic tremor was observed before many vulcanian explosions. Though harmonic tremor is relatively common at volcanoes, the high fundamental frequency of these tremors (up to 30 Hz) is unique and of particular interest. Hotovec et al. (JVGR, 2013) linked this tremor to rapidly repeating magnitude ∼1 earthquakes located a few kilometers beneath the vent. These events might be occurring as brittle failure of the magma or as slip along the margins of an obstruction within the conduit. Using a frictional faulting model, Dmitrieva et al. (Nature Geoscience, 2013) converted the seismicity and tremor signals into an estimate of the history of shear stresses acting on the fault surface and causing slip. Stressing rates increased, in a nonlinear manner, from less than 1 MPa/s to about 20 MPa/s over the final ten minutes before the explosions. Here we investigate what conduit processes could plausibly be responsible for such high stressing rates.

One possibility is that a blockage develops in the conduit prior to each explosion, perhaps from a crystal-rich magma plug or collapse of the conduit walls. This obstacle temporarily prevents upward flow of magma, while deeper influx from below thus compresses and pressurizes magma in the conduit beneath the blockage.

Through numeric modeling of this system, we find that as magma accumulates within the conduit beneath the blockage, pressure on the base of the obstruction (which, through force balance, is proportional to shear stress on its margins) rises in a nonlinear manner. This is because the effective compressibility of the system decreases as the exsolution depth rises in response to increasing pressure. Preliminarily results suggest that this model can reproduce the nonlinear increase toward the very high stressing rates inferred from the seismicity and tremor data, without requiring additional temporal variations in deep magma chamber pressure.

Using Spatial Density Estimates to Assess Volcanic Hazards in Dominica, Lesser Antilles

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Risk posed by volcanic eruptions are generally stemmed in a few ways; in the short term geophysical data such as seismic activity or ground deformation are used to assess the state of volcanic unrest in the short term while statistical approaches such as spatial density estimates are used for long term hazard assessment. Spatial density estimates have been used in a number of monogenetic volcanic fields for hazard map generation and uses the age and location of previous eruptions to calculate the probability of a new event occurring at a given location within this field. In a previously unpublished study, spatial density estimates of the Lesser Antilles volcanic arc showed the island of Dominica to have the highest likelihood of future vent formation. In this current study, this technique was used in combination with seismic and geodetic data to generate a hazard map for Dominica which not only takes into consideration the past events but also its current state of unrest. Here, geophysical data served as a weighting factor in the estimates with those centers showing more vigorous activity receiving stronger favorability in the assessment. In addition to this weighting, the bandwidth utilized in the 2D-radially symmetric kernel density function is varied so as to find the value which best minimizes the error in the estimate. The end results of this study are dynamic volcanic hazards maps which will be readily updatable as changes in volcanic unrest occurs within the system.

The Subtle Beginning of an Earthquake Swarm Beneath Long Valley Caldera, California, Detected by Downhole Seismometers

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Swarm activity in Long Valley caldera is often correlated with resurgent dome inflation. From 1980 to 1999 recurring swarms in the South Moat Seismic Zone were accompanied by 80-cm of dome uplift. The caldera has been relatively quiet since 2000, except for two gradual uplift episodes: one episode in 2002–2003 and one ongoing episode that began in 2011. Since 2011, we have observed uplift at about half the rate of the mid-1990's uplift, and a renewal of swarm activity. While swarms have occurred more frequently since uplift resumed, two recent swarms in Oct./Nov. 2012 and Mar. 2013 are the focus of this study. They were accompanied by short deformation transients during which caldera uplift paused for about a week.

To better understand this recent activity, we cross correlate waveforms from catalog earthquakes to identify similar clusters (families) of events from the borehole seismometers in the Long Valley Exploratory Well (MDH1). MDH1 instrumentation includes two three-component seismometers, located 2592 m and 2263 m below ground level. Then we use representative waveforms from each family as templates to search the continuous waveforms for smaller earthquakes. The cross correlations identify ∼25 times more earthquakes than triggered from surface stations. Most of the added earthquakes have magnitudes ranging from −1 to +0.5, determined from an empirical relationship between catalog magnitude and amplitude observed at MDH1. We compare the detected repeating earthquakes to a typical short/long-term average trigger and find that the detected repeating earthquakes comprise about 95% of the swarm events. The borehole instruments detected three small events with waveforms highly correlated with the most common swarm family, ∼15 s before the first earthquake to trigger on the surface network. This observation suggests that the swarm begins with small chattering, in contrast to mainshock-aftershock sequences that start with the largest event.

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