SEISMOLOGICAL GRAND CHALLENGES IN UNDERSTANDING EARTH'S DYNAMIC SYSTEMS

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EXECUTIVE SUMMARY

S eismology is the study of Earth's elastic vibrations, the sources that generate them, and the structures through which they propagate. It is a geophysical discipline that has a remarkable diversity of applications to critical issues facing society and plays a leading role in addressing key scientific frontiers involving Earth's dynamic systems. Seismology enjoys quantitative foundations rooted in continuum mechanics, elasticity, and applied mathematics. Modern seismological systems utilize state-of-the-art digital ground motion recording sensors and real-time communications systems, and anyone can openly access many seismological data archives.

Seismologists "keep their ear" on Earth's internal systems, listening for signals arising from both natural and human-made energy sources distributed around the globe. These seismic signals contain a wealth of information that enables seismologists to quantify active wave sources and determine structures and processes at all depths in the planetary interior. This is done at higher resolution than is possible by any other approach, revealing structures associated with dynamic processes that are active now or have been ongoing over multibillion years. Recent breakthroughs in theory and data processing now allow every byte of continuous seismological data acquired to be used for imaging sources and structures throughout these dynamic systems, even extracting coherent signals from what had previously been dismissed as background noise. Ground-motion recordings are intrinsically multi-use; seismic data collected to monitor any specific Earth phenomenon, for example, underground nuclear tests, can also advance studies of earthquake sources or deep Earth structure. This multi-use attribute of seismic data places great value in the prevailing philosophies of open data access and real-time data collection embraced by the U.S. seismological research community and many of its international partners.

A rich panoply of societal applications of seismology has emerged directly from basic research programs focused on understanding Earth's active wave sources and structure. Seismology plays central roles in hydrocarbon and resource exploration, earthquake detection and quantification, earthquake hazard assessment and strong ground motion prediction for the built infrastructure, including lifelines and critical facilities, volcanic-eruption and tsunami-warning systems, nuclear test monitoring and treaty verification, and aquifer characterization. Seismology provides unique information about glacier systems, landslide mass movements, the ocean wave environment, containment of underground wastes, carbon sequestration, and other topics relevant to climate and environmental change.

A 2008 workshop on seismological research frontiers, funded by the National Science Foundation (NSF), considered promising research directions for the next decades and identified the following 10 Seismological Grand Challenge research questions:

- How do faults slip?
- How does the near-surface environment affect natural hazards and resources?
- What is the relationship between stress and strain in the lithosphere?
- How do processes in the ocean and atmosphere interact with the solid Earth?
- Where are water and hydrocarbons hidden beneath the surface?
- How do magmas ascend and erupt?
- What is the lithosphere-asthenosphere boundary?
- How do plate boundary systems evolve?
- How do temperature and composition variations control mantle and core convection?
- How are Earth's internal boundaries affected by dynamics?

Further seismological research on these questions will address both fundamental problems in understanding how Earth systems work and augment applications to societal concerns about natural hazards, energy resources, environmental change, and national security. Seismological contributions, research frontiers, and required infrastructure for progress on these 10 Seismological Grand Challenges are described in this report. Selected examples of recent research advances are used to highlight rapid progress, outstanding challenges, and diverse applications of seismology for studying Earth's dynamic systems. The essence of associated seismological practices and approaches are further defined in an appendix by discussion of two key disciplinary practices: (1) monitoring the full diversity of dynamical processes in Earth's environment, including human-induced sources and processes, and (2) multiscale, three-dimensional (3D) and time-varying (4D) imaging and modeling of Earth's complex systems.

Maintaining a healthy national research capability in seismology to pursue the many societally important applications of the discipline and to address the 10 Grand Challenge research questions requires sustained and expanded support of seismic data acquisition, archival, and distribution facilities. Global and regional seismological networks with a commitment to long-term operation, and pools of portable instruments for shorter-term land- and sea-based deployments, provide key observations essential to tackling the Grand Challenges. The Advanced National Seismic System (ANSS), the primary earthquake monitoring system in the United States, must be completed. The currently sparse instrumental coverage of the vast areas of unexplored ocean floor needs to be expanded. Source facilities for controlled-source seismic data acquisition are essential to support crustal reflection and refraction imaging, including marine airguns, explosions in boreholes, and vibrating trucks. Cooperation among academic, government, and industry efforts in controlled-source seismology must be enhanced to support the Grand Challenge efforts. Completion of the planned deployment of the EarthScope Transportable Array across the conterminous United States and Alaska is important for achieving the manifold science goals of that major NSF program. International participation in open seismic data exchange for diverse seismic networks around the world must be diplomatically pursued and expanded. Interdisciplinary workshops addressing critical problems of the near-surface environment and deep Earth should be promoted, with active seismological participation.

Many of the government and private sector users of seismology are now confronted with serious workforce shortages. Expanded efforts are required to attract quantitatively oriented, diverse students to the discipline. These efforts should be abetted by building on current education and outreach endeavors of the seismological community, and by developing stronger partnerships among academic, industry, and government laboratories, which are all impacted by workforce-shortage issues. At the same time, some trends toward reducing seismological staff and resources in government labs need to be reversed to sustain contributions of the discipline.

Seismology holds great promise for achieving major breakthroughs on the Seismological Grand Challenge questions and associated societal benefits over the next few decades, as long as federal agencies and industry continue to invest in basic research programs and infrastructure for this burgeoning geophysical discipline. With the well-established practices of open data sharing, expanding efforts to share software and to develop community models, and the multi-use aspect of all seismic data, bountiful return on investments in seismological infrastructure and training is assured. As progress on the Seismological Grand Challenges is made, the fundamental understanding of Earth's dynamic systems that is gained will advance the sustainability and security of human civilization, along with satisfying our deep curiosity about how planet Earth works.

INTRODUCTION

THE SEISMOLOGICAL DISCIPLINE

The ground beneath our feet usually seems solid and unmoving, but in reality it is in a constant state of vibration; only intermittently are the motions strong enough for human perception. Sensible motions may involve small vibrations from a large truck passing nearby or possibly shaking from a distant earthquake. On occasion, the ground moves violently, causing catastrophic loss of life as buildings collapse and Earth's surface is disrupted. These ground motions originate in Earth's rocky interior by various processes that suddenly release stress, such as rapid sliding motions across a fault. The stress change produces propagating disturbances that expand outward from the energy source through the surrounding rocks in the form of elastic P-waves and S-waves that reach and shake the surface.

About 140 years ago, scientists first invented instruments to record seismic vibrations of the ground as a function of time, and geophysicists drew upon solid mechanics and elasticity to develop fundamental understanding of elastic waves. This was the beginning of the discipline of seismology, which involves the study of seismic waves, their sources, and the medium through which they propagate. Because it is a discipline that infers source and structural information from remotely observed data, the field has driven many mathematical methods for inversion and inference. Seismology provides quantitative models for structures and sources that guide many multidisciplinary Earth science research and monitoring efforts. During the twentieth century, the discipline grew into

a major international endeavor, developing a panoply of applications of Earth's vibrations. These applications study both the dynamic sources of the seismic waves and the characteristics of the materials through which they travel along with myriad industrial, societal, and scientific applications.

Placing ground motion sensors, or seismometers, on Earth's surface is akin to putting stethoscopes on the Earth system and listening for the rumblings and gurglings of the planet's internal processes. Over the past century, seismologists have learned to unravel the rich information contained within seismograms, applying quantitative elastic (and nonlinear) wave theory to accumulating databases and distilling meaningful information from the cacophony of seismic motions. Classic seismological applications include the systematic location and quantification of earthquakes and construction of models for Earth's elastic wave properties as functions of depth from the surface to the center of the planet. This dual effort to study both earthquake sources and Earth structure is now advanced but still frames the discipline.

Controlled human-created energy releases, such as buried explosions, underwater airguns, and large vibrating trucks, provide seismic wave sources at Earth's surface that illuminate the shallow crust with elastic waves. These active-source techniques are analogous to ultrasound methods used in medical imaging, and provide very high resolution of subsurface conditions and the detection of energy and mineral

resources. Seismology intrinsically provides unparalleled resolution of physical properties in the inaccessible interior from the crust to the core. Seismic imaging of fossil-fuel-bearing geologic structures is essential to discovering, exploiting, and managing critical energy resources that power global civilization. When nuclear testing moved underground during the Cold War, seismology assumed a key role in treaty verification and in remote monitoring of weapons development programs.

With these new roles in hydrocarbon exploration and national security monitoring efforts complementing earthquake studies and Earth structure research, seismology rapidly grew into a major high-tech research discipline. Today, global seismometer networks transmit ground motion recordings from around the world in real time via satellite, microwave, or Internet telemetry to data analysis centers. Automated computer processing of the accumulated seismic signals is performed by many government agencies and research programs to produce rapid bulletins of global seismicity and prompt information for disaster mitigation. These activities are essential for the continuous monitoring of the Earth system, and there is still much room for improvement of methodologies used in many efforts. Large-scale deployments of land- and sea-based instruments utilize both active human-made sources and passive natural sources of seismic waves, revealing multiscale structures of the crust and deep Earth. Massive online data repositories freely provide the data to scientists, enabling research and monitoring applications across academic, government, and commercial sectors. The complexity of seismic wave processing and modeling efforts combined with very large seismic data sets has placed seismology as a primary driver of high-performance computing at universities, national laboratories, and industry for many decades.

International Federation of Digital Seismograph Networks

11/2008

GSN   Australia   Canada   France   Germany   Italy   Japan   U.S.   Other
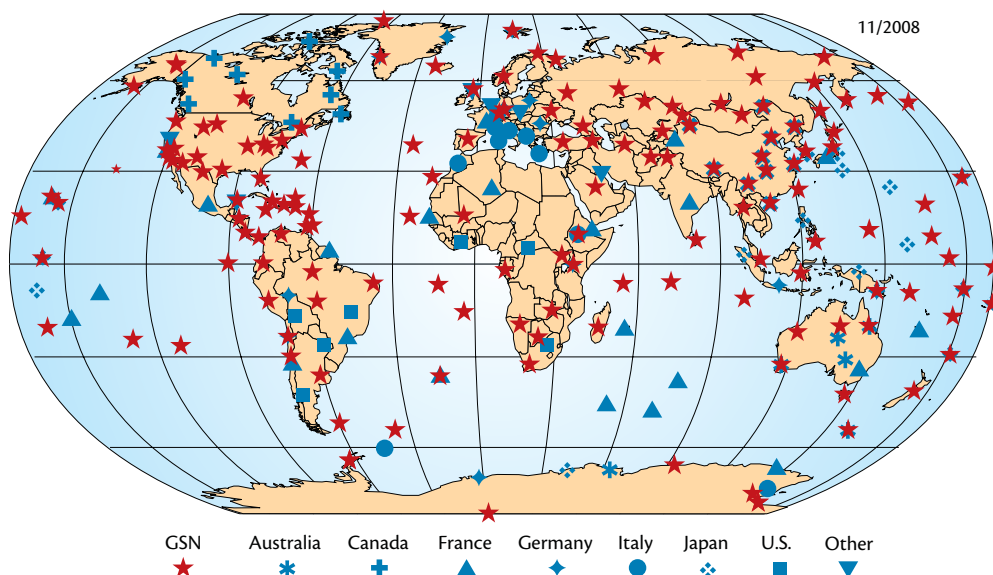
The global reach of seismology is exemplified by this map of the distribution of high-quality broadband "backbone" seismic stations of the International Federation of Digital Seismograph Networks (FDSN), which includes the IRIS/USGS Global Seismographic Network (GSN). (Image courtesy of R. Butler.)

A defining attribute of seismograms is that they are simply records of ground motion as a function of time. Thus, seismic data recorded by a network of seismometers for any particular purpose (e.g., monitoring nuclear testing or earthquake hazard analysis), intrinsically provide signals that are valuable for multiple unrelated uses. One can equally well study Earth structure, earthquakes, explosions, volcanic eruptions, and other processes with the same seismograms. Study of the diverse Earth systems requires globally distributed sensors and international collaborations on data acquisition and exchange. The multi-use attribute of seismic signals places a great premium on continuously recording ground motions over as wide of a frequency band as possible, archiving all recordings in accessible formats, and openly sharing the data between nations and institutions, no matter what the original motivation was for deploying the seismic instrumentation. The U.S. seismological community, and its international partners in the Federation of Digital Seismograph Networks (FDSN), have strongly fostered this framework of open access to seismic data, establishing data centers that are accessible to all researchers. Because the data play critical roles in rapid evaluation of short-term changes in Earth's dynamic systems (e.g., earthquakes, tsunamis,

volcanic eruptions, explosions, mine collapses, rock bursts, landslides) that have very long-term negative impacts on human life, property, and infrastructure, near-real-time access to seismic data is also of great importance. Whenever it is possible to transmit ground motion data to open archives in real time, multiple societal applications of the signals are enabled.

By its very nature, seismology is sensitive to many active, dynamic processes happening today in Earth's dynamic systems, and the discipline has expanded its scope to include detecting and characterizing numerous aspects of environmental change and near-surface processes, including ground-water distribution, glacial motions, storm migration, the ocean wave environment, and ocean circulation. Much of modern Earth science research addresses complex physical systems that involve interfaces among multiple disciplines, and seismology offers powerful tools for remote sensing of structures and sources that complement other approaches. This central importance of seismology is noted in many major scientific planning documents (e.g., BROES, 2001; IUGG, 2007), and a suite of research community organizations (CIDER, COMPRES, CSEDI, FDSN, IASPEI, IAVCEI, IRIS, MARGINS, RIDGE, SCEC, UNAVCO—all
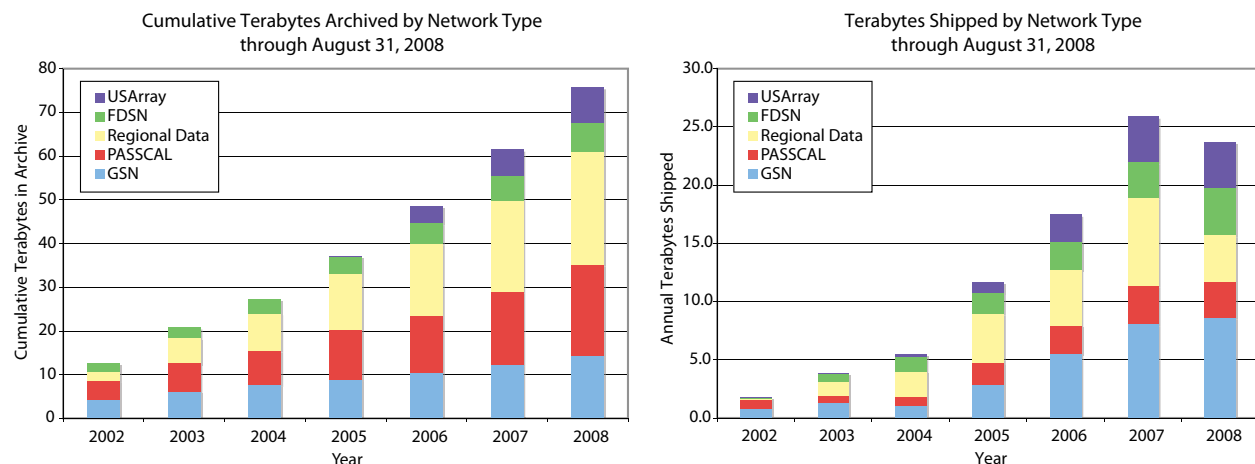
The cumulative volume of seismic data archived at the IRIS Data Management Center (left) for major seismic networks totals 81.3 terabytes as of August 2008. The annual number of terabytes shipped from the IRIS DMC (right) for the same seismic network types is twice as much data as new data arriving at the DMC, and will total more than 35 terabytes to end users in 2008. (Image courtesy of T. Ahern.)

acronyms are defined at the end of the report) engage seismologists with synergistic disciplines in mineral physics, geodynamics, volcanology, geology, and increasingly, oceanography, hydrology, glaciology, climate, and atmospheric sciences.

This centrality of seismology in Earth science and global monitoring engages multiple U.S. federal agencies in supporting the discipline, including the National Science Foundation (NSF), the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE), the Department of Defense (DoD), the Federal Emergency Management Agency (FEMA), and the National Aeronautics and Space Administration (NASA). This diversity of supporting agencies has benefited the discipline immensely, and reflects the multi-use nature of seismological data. U.S. seismology is deeply engaged in international activities such as the International Monitoring System (IMS) of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), and the Global Earth Observations System of Systems (GEOSS), placing the discipline in high-level, scientifically and politically influential roles.

One sign of a healthy scientific enterprise is that it is producing major advances and paradigm shifts. As manifest in this report, seismology is a dynamic and energized field, with a continually expanding portfolio of important contributions. Examples of recent transformative developments in the discipline include the following:

• Creation of the open-access online seismic data repository of the Incorporated Research Institutions for Seismology (IRIS) Data Management System (DMS) has enabled proliferating discoveries and new societal applications by many researchers. This facility, which houses terabytes of seismic data, freely delivers these data to the entire world, an approach being emulated internationally.
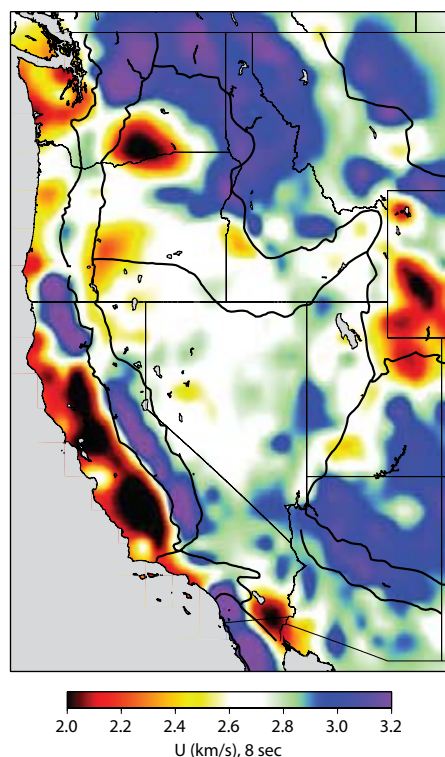
A map showing variation of Rayleigh wave (a type of seismic surface wave) group velocity for 8 sec period vibrations derived from more than 60,000 measurements. By cross correlating up to three years of continuous data from 512 western U.S. stations, including the EarthScope USArray Transportable Array and regional seismic networks, inter-station propagation velocities for all available station pairs were recovered and inverted for regional velocity structure. Thick black lines define major tectonic province boundaries. (Image courtesy of M.P. Moschetti, M.H. Ritzwoller, and N.M. Shapiro.)

• The availability and centralized maintenance of large pools of state-of-the-art portable seismographs, such as IRIS PASSCAL, has driven a new era of discovery in seismic source and structural studies across the discipline.

• The discovery of coherent information contained in recorded seismic "noise" allows virtually every data byte to be used for scientific application; entirely new approaches to structural studies and investigations of changes in the oceanic and atmospheric environment have emerged. Earth's background vibrations contain information about sources and structures that was not recognized until recently.
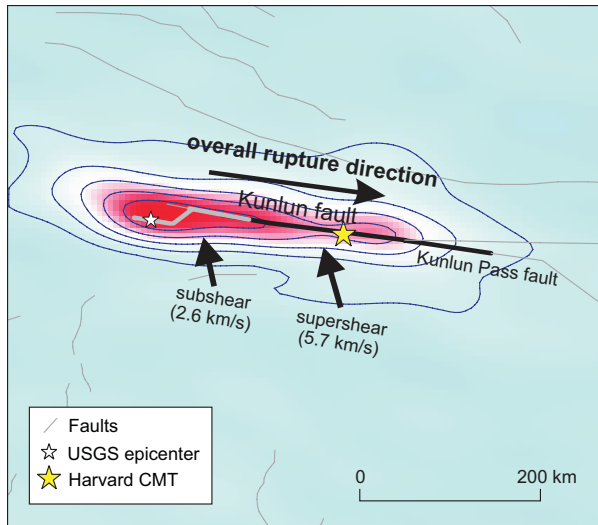
The 2001 Kokoxili (M_w 7.8) earthquake ruptured about 400 km of the Kunlun fault in northern Tibet and is one of the longest strike-slip events recorded by modern seismic networks. The contours indicate the intensity of high-frequency seismic radiation as imaged using back-projection of globally recorded P-waves, with the strongest regions plotted in red. Analysis shows that the rupture propagated at ~ 2.6 km/s for the first 120 km and then accelerated to ~ 5.7 km/s, a super-shear (faster than S-wave speed) velocity that continued for at least 290 km away from the epicenter. (Image courtesy of K.T. Walker and P.M. Shearer.)

• The recent discovery of a continuous spectrum of faulting behavior, ranging from conventional earthquakes that rupture at great speeds (including supershear velocities) to "slow earthquakes" that involve anomalously slow ruptures—some so slow that the sliding motion does not radiate detectable seismic waves or is manifested in seismic tremor—has unified seismic and geodetic monitoring of fault zones and may have fundamental importance for frictional sliding processes and earthquake hazard.

• The discovery of the predominance of large-scale structures with anomalous elastic properties in the deep mantle by imaging methods (e.g., seismic tomography) has brought a paradigm shift to our understanding of mantle convection and thermal evolution of Earth's deep interior, with new emphasis on thermo-chemical dynamics.

• Project EarthScope, a major research effort funded primarily by NSF, is providing unprecedented spatial coverage of seismic and geodetic observations
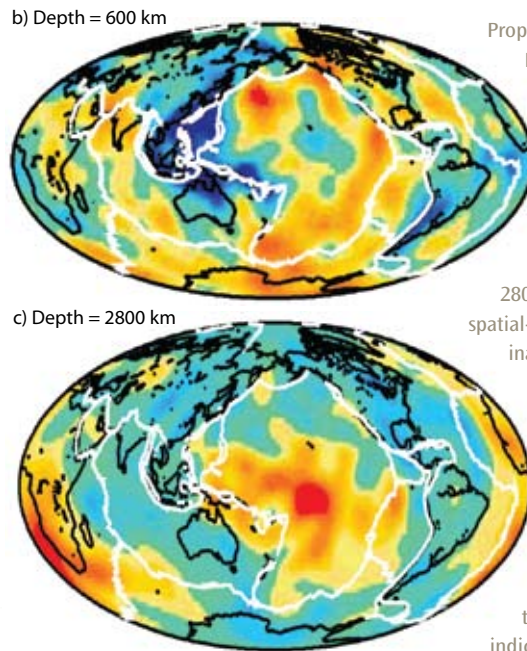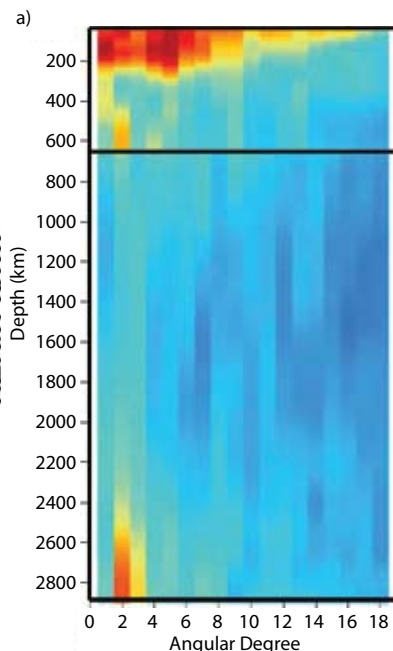
Properties of a recent 3D S-wave velocity Earth model showing (a) the power spectrum of velocity variations as a function of angular degree (inversely proportional to spatial scale) and depth; red is high power, blue is low power. Shear velocity anomalies at (b) 600-km depth, (blue is fast, red is slow; scale range is ± 2%), and at (c) 2800-km depth (scale range is ± 3%). Large-spatial-scale (angular degree 2) patterns dominate at both of these depths, likely due to accumulations of slabs near 600 km and the presence of two large-low-shear-velocity provinces under Africa and the Pacific and a continuous ring of higher than average velocities beneath the circum-Pacific near 2800-km depth. The unexpected dominance of very large-scale structure with anomalous seismic velocities indicates the importance of thermo-chemical convection in the mantle (Image courtesy of B. Kustowski, G. Ekström, and A. Dziewonski.)

across North America, revealing fine-scale crustal and mantle structures that are divulging secrets of continental evolution.

• The emergence of quantitative physics-based predictions of surface ground motions using realistic dynamic fault rupture models and 3D geological structures has begun to transform earthquake hazard analysis, complementing the emergence of performance-based earthquake engineering.

• The discovery of remote triggering of earthquakes and enhanced understanding of earthquake interactions has provided new insights into the stress changes that lead to earthquake initiation.

• The tsunami generated by the great 2004 Sumatra earthquake reaffirmed the catastrophic potential of natural events and the need for early-warning systems. Automated data collection and processing are enabling near-real-time responses to earthquake occurrence, including seismic shaking and tsunami-warning systems that have potential to save many lives.

The continued health and vigor of seismology requires federal and industry attention to critical foundations of the discipline and expansion of the base upon which future advances can be built. Core needs include sustaining and expanding data collection and dissemination infrastructure, providing access to high-performance computational resources, attracting and supporting diverse, quantitatively oriented students to the discipline, and fostering interdisciplinary collaborations to study complex Earth systems. To clarify the critical functions and potential contributions that seismology can make and the infrastructure needed to achieve the full span of possibilities, the seismology community has identified 10 Grand Challenge research questions for the next few decades and the associated infrastructure needs essential for making progress on these topics.
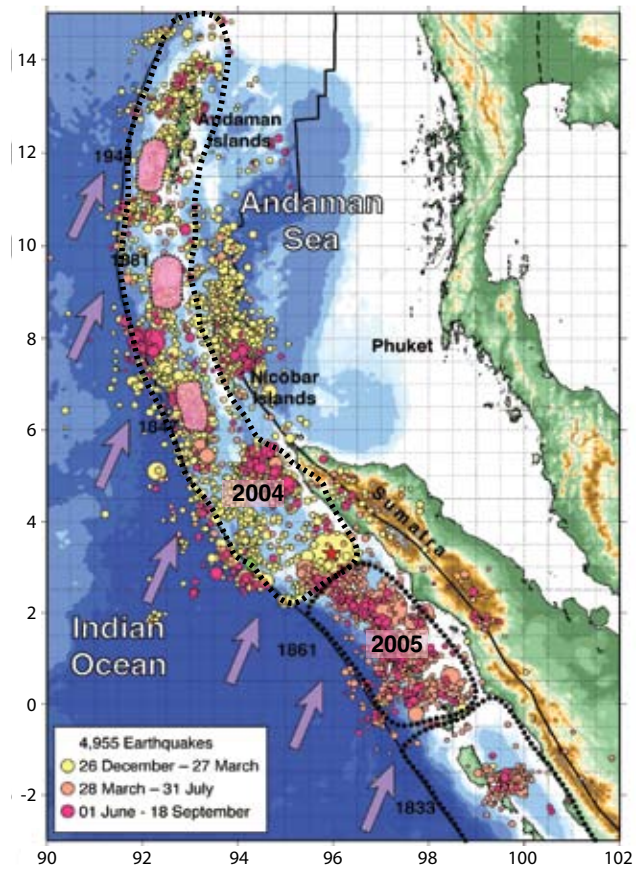
Rupture zones of the 26 December 2004 (seismic moment magnitude M_w = 9.2) and 28 March 2005 (M_w = 8.7) great Sumatra earthquakes. The 2004 event generated a tsunami that claimed over 225,000 lives around the Indian Ocean. International teams of seismologists and geodesists have studied how the rupture spread over the fault, how slip varied along the subduction zone, and how aseismic after-slip occurred for several months after the events. Efforts to establish new tsunami-warning systems for the Indian Ocean and Caribbean are now underway. (Image courtesy of C.J. Ammon.)

GRAND CHALLENGES FOR SEISMOLOGY

T he history of seismological advances has validated the approach of sustaining diverse basic science research in seismology as the most effective way of developing and enhancing the societally critical applications of the discipline. This strategy ensures workforce education in university programs, incorporation of novel technologies and innovations into seismological practices and operations, and cultivation of fertile ground for serendipitous discoveries that can create whole new areas of application. Here, the seismological research community has defined ten major Grand Challenge questions at the forefront of research on Earth systems to which seismology contributes significantly. These Grand Challenges are framed by fundamental research issues, but encompass hazard mitigation, environmental monitoring, and resource-extraction efforts of central importance to society and supported by many federal and state agencies.
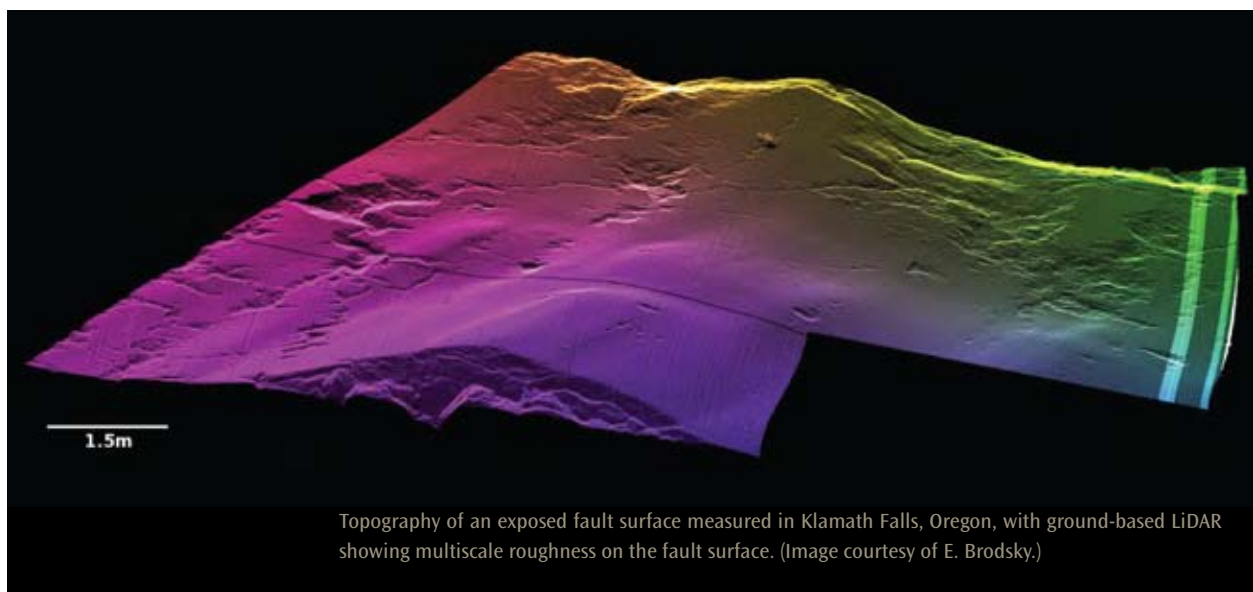
GRAND CHALLENGE 1.
HOW DO FAULTS SLIP?

The general public associates seismology mainly with earthquakes, making it one of the most widely recognized of Earth science disciplines. Understanding the nature of earthquake faulting continues to be a top priority seismological undertaking that holds many implications for society. The steady relative motions of Earth's tectonic plates concentrate stresses that are relieved mainly as slippage along faults on plate boundaries and within their plate interiors. Multiscale fault zone systems, ranging from the microscopic to the scale of plate boundaries, are involved in earthquake initiation, rupture, and termination. Seeking a detailed physical understanding of the nonlinear processes by which faults slip in these complex systems is a demanding Grand Challenge for seismology.

The sliding motion of faults exhibits a huge range of complex behavior. The most spectacular releases of stress occur in conventional earthquakes. Elastic potential energy stored up in the rock over hundreds to thousands of years as a result of adjacent relative plate motions, is rapidly released when fault frictional resistance is overcome; local shearing motions occur within seconds, generating seismic waves that radiate outward. Recent observations reveal a rich spectrum of additional fault slip behavior, from faults that offset steadily without apparent resistance, to faults that slide sporadically, chattering as they slip in sequences of numerous overlapping events, to others that slide at super-shear velocities (faster than the speed of S-waves in the rocks), emitting seismic shock waves that can cause large, exceptionally damaging ground motions.

Seismology provides many of the highest-resolution tools for peering into fault zones. Seismic recordings can be used to image the geometry and time-dependent properties of the fault zones in diverse environments, although current models make many simplifying assumptions such as "faults are planar" or "slip is unidirectional," which are likely not always correct. Variations of fluid concentrations

Topography of an exposed fault surface measured in Klamath Falls, Oregon, with ground-based LiDAR showing multiscale roughness on the fault surface. (Image courtesy of E. Brodsky.)

and pressures along fault zones play important roles in frictional behavior, and seismological efforts have succeeded in imaging fluid distributions at depth. Catalogs of the locations of massive numbers of tiny to moderate earthquakes, accurate within tens of meters, reveal diverse frictional behavior among faults and along a single fault surface. Persistent alignments of small earthquakes on faults have been discovered by precise event locations, and many examples of virtually identical earthquakes recurring at the same location on a fault have been studied. Global and regional arrays of seismic stations and deep borehole seismic instruments like those deployed in the EarthScope SAFOD drill hole, provide recordings that capture the initiation, growth, and termination of fault ruptures. Resulting kinematic and dynamic faulting models constrain physics-based theoretical models that are used to predict strong shaking, at least in a probabilistic

sense. Among the most exciting Earth science discoveries of the past decade have been the coupled phenomena of slow slip events (detected geodetically) and seismic tremor. The slow slip process appears to represent a frictional behavior intermediate between that of steady sliding and stick-slip earthquakes. Seismic fault tremor, a low-level seismic rumbling with extended duration, correlates with slow slip in some environments and may be a superposition of many individual subevents, but its nature is still being investigated.

Seismology has made great progress in the basic understanding of how and where faults are likely to fail, but there is currently no reliable method for producing short-term warnings of an impending earthquake. The insights gained have provided useful seismic hazard assessments for land-use planning, as guidance for construction standards, and for planning

Seismicity

Seismic monitoring systems detect and locate thousands of earthquakes globally every year, most of which go unnoticed by the public. The resulting earthquake catalogs prepared by universities, the USGS, the International Seismological Centre (ISC), and many international organizations are extensively used for seismic hazard analysis and basic research applications. The map on the left shows locations of 82,000 earthquakes along the San Andreas Fault system between 1984 and 2003, detected by a dense regional seismic network. The seismicity distribution reveals properties of faults and how these change in space and time. Many events occur where no faults are mapped at the surface, revealing hidden fault zones. New procedures for locating these events provide very precise relative locations, sometimes with uncertainties as small as a few meters, thus illuminating faulting process in unprecedented detail. For the region of central California shown in the map on the right, 12% of all recorded earthquakes occurred on faults that failed multiple times during the

19-year observation period. Repeating earthquakes tend to concentrate along faults that are largely creeping. This observation suggests that tiny asperities on these otherwise steadily sliding faults strengthen rapidly—within days to a few years—so that they can become re-stressed by the nearby ongoing slip. (Image modified from F. Waldhauser and D.P. Schaff, 2008. Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *Journal of Geophysical Research*, 113, B08311, doi:10.1029/2007JB005479.)

High Resolution Epicenters

Repeating Earthquakes

Min. Number of Repeats
- 2
- 5
- 10
- 20
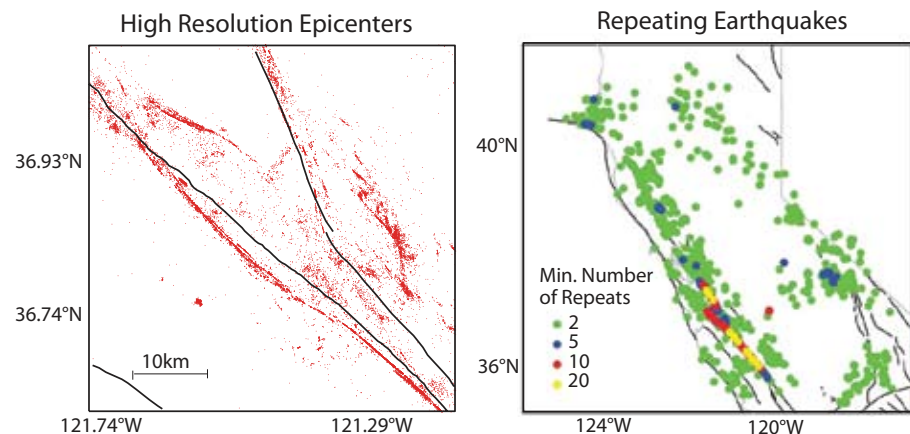
for emergency response. Far more can be achieved by enhancing our fundamental level of observations and understanding of the physics of earthquake ruptures, ranging from better prediction of ground shaking variations, to expansion of early warning systems for earthquake and tsunami hazards.

KEY QUESTIONS AND ISSUES

- What physical properties control diverse types of fault sliding?
- How does the relationship between local conditions at a point on a fault and conditions over the whole fault surface evolve?
- Is there a preparatory stage for fault ruptures? How do ruptures stop?

- Are mechanisms of interplate and intraplate earthquakes different?
- What frictional constitutive laws govern faulting variability, and how are frictional properties different for high-speed slip? What governs transitions from stick-slip behavior to steady sliding?

Earthquake Rapid Warning Systems

Before a future earthquake, you might get a warning. Maybe not much of a warning—perhaps a few seconds or a few tens of seconds at best. But it may be enough time to allow you to dive under that table, move away from that bookcase, or step back from that window. Your train could slow or stop and the highway on-ramp meter lights could turn red. Nuclear power plants could lower their control rods while refineries isolate tanks and vulnerable pipelines. With sufficient investments to link modern digital seismic networks and communication systems with decision-making systems and clear regulatory guidelines, a warning can be provided that comes before strong shaking starts at your location. This scenario is now plausible by very rapidly detecting earthquakes, locating and estimating their completed or potential energy release, and alerting surrounding regions after the earthquake has started but before the seismic waves reach regions away from the earthquake source. In fact, the first steps in earthquake early warning have already been taken in some parts of the world. In October 2007, Japan launched the first national earthquake warning system. The system uses a network of over 1000 seismic stations linked together to detect earthquakes ruptures automatically after they have initiated and while sliding may still be underway, and issue immediate warnings to the public. Taiwan, Turkey, Mexico, and Romania also have limited warning systems in place, and many other countries, including the United States, have prototype systems under development, but major investments will be required to make these systems operational. Dense geophysical
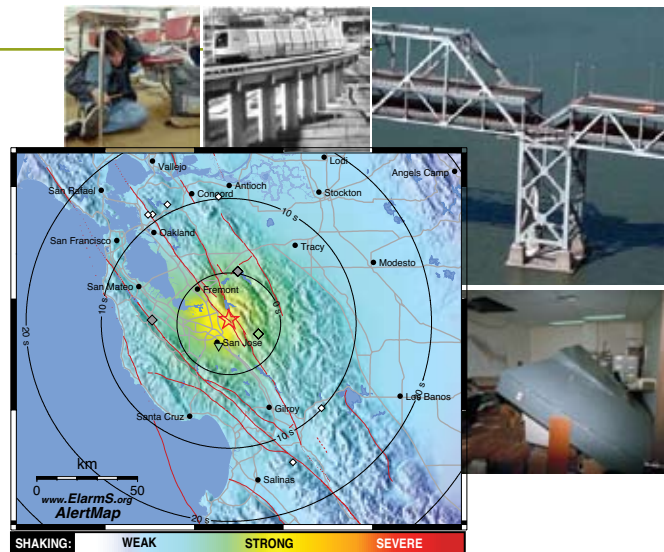
Earthquake warning AlertMap showing the predicted distribution of ground shaking for the October 30, 2007, M_w 5.4 earthquake near San Jose, California. The test system detected the earthquake and assessed the hazard before ground shaking was felt in San Francisco. Photos show the type of damage that large events, such as the 1989 Loma Prieta earthquake, have caused in the region. (Image courtesy of R. Allen.)

instrumentation in earthquake source regions is required, with rapid and robust telemetry, and automated processing. Similar strategies underlie enhanced tsunami-warning systems, which exploit the fact that the sea wave generated by an underwater earthquake travels at less than the speed of a jet airplane, much slower than seismic waves traveling through rock.
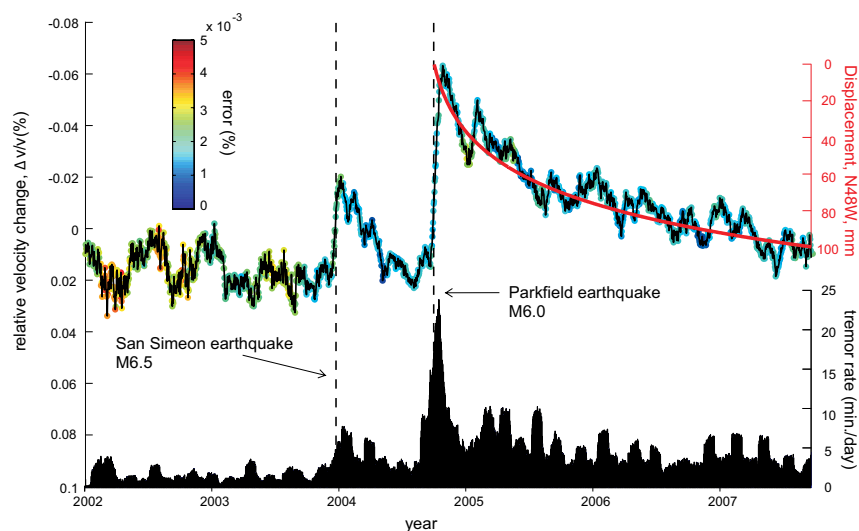
- What is the fundamental nature of high-stress asperities (areas of high-slip in an earthquake) and the cause of friction variations?
- How is episodic fault tremor and slip related to large earthquake occurrence?
- How do earthquake rupture zones recover and reload?
- How do large and small earthquakes fundamentally differ, if they do?
- Can rupture directions and associated ground motions be anticipated based on material properties?

- What are the geometrical properties of fault distributions and how do fault networks and fault surfaces evolve over time?
- Can we forecast the spatial and temporal occurrence of earthquakes and accurately predict their effects on ground motions and on the built environment?
- How quickly can the size of an earthquake be determined and reliable shaking and tsunami warnings issued?

Ambient Noise and Fault Zone Healing

Cross-correlating long records of microseismic noise between two stations can determine properties of the intervening medium, providing a powerful probe of structure, and when performed over time, temporal changes in the structure. An exciting application of this approach is to monitor temporal changes in velocity structure in and around fault zones, especially when a large earthquake occurs. The figure shows changes in the medium along the San Andreas Fault, near Parkfield, California, with velocity reductions correlating with the San Simeon earthquake (off the fault) and the Parkfield earthquake (on the fault). The gradual increase in along-fault seismic velocity following the earthquakes suggests that the fault is damaged by the shear strain and seismic waves from the earthquake, and the medium recovers (heals) over time. The red line shows an empirical correspondence with Global Positioning System (GPS) measured displacement along the fault; the filled-in black lower plot is the amount of nonvolcanic tremor (low-frequency vibrations from nearly continuous fault sliding) occurring over time as measured by local seismometers. The correspondence of the along-fault velocity structure, surface displacement, and nonvolcanic tremor suggests stress relaxation in the part of the fault zone at greater depth than the coseismic rupture. (Image from M. Brenguier, M. Campillo, C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, and E. Larose, 2008. Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations, *Science*, 321(5895):1478–1481, doi:10.1126/science.1160943. Reprinted with permission from AAAS.)

- Deploy more sensitive and low-noise seismographic arrays in shallow boreholes near faults.
- Maintain large pools of portable instruments for rapid deployment after earthquakes.
- Collect strong ground motion recordings for more large earthquakes.
- Sustain long-term operation of global and regional networks.

- Perform real-time analysis of earthquake source properties for rapid earthquake and tsunami warning systems.
- Increase communications and collaborations with other disciplines studying aspects earthquake science, such as drilling efforts, geological studies, and laboratory studies.

Episodic Tremor and Slip (ETS)

Significant earthquake hazard results from subduction of an oceanic plate beneath the Cascadia-Vancouver Island region straddling the US-Canadian border. Only within the past decade has it been discovered that this collision between continental and oceanic plates is accompanied by surprisingly regular episodic tremor and slip. The deployment of networks of strain, seismic, and geodetic instruments in Cascadia as part of project EarthScope has enabled scientists to unravel the details of how this slow slip and tremor co-evolve. For example, the locations of seismically observed tremor from the January 2007 ETS event (circles colored by date) show a 10 km/day northward migration and coincide with geodetically inferred slip of a few centimeters (lighter area on the gray shaded plate interface). Most of the relative plate motion in the slow slip area is accommodated by similar slip events that repeat every 14 months. Plate boundary slip in the "locked zone" to the west of the contours of partial locking occurs during great earthquakes such as the M = 9 Cascadia megathrust earthquake in 1700. Analyses of strainmeter data are beginning to show a migration of slow slip that appears to track the tremor path. Most models of slow slip associate its occurrence with a region transitional between where the plate is locked and where it is sliding continuously at greater depth. This new picture of slow slip and tremor suggests that the locked zone of the plate interface, and probable region of strong ground motion during future earthquakes, extends significantly further inland than had been thought, closer to the large population centers of Cascadia. (Image courtesy of K. Creager.)

Episodic Tremor and Slip
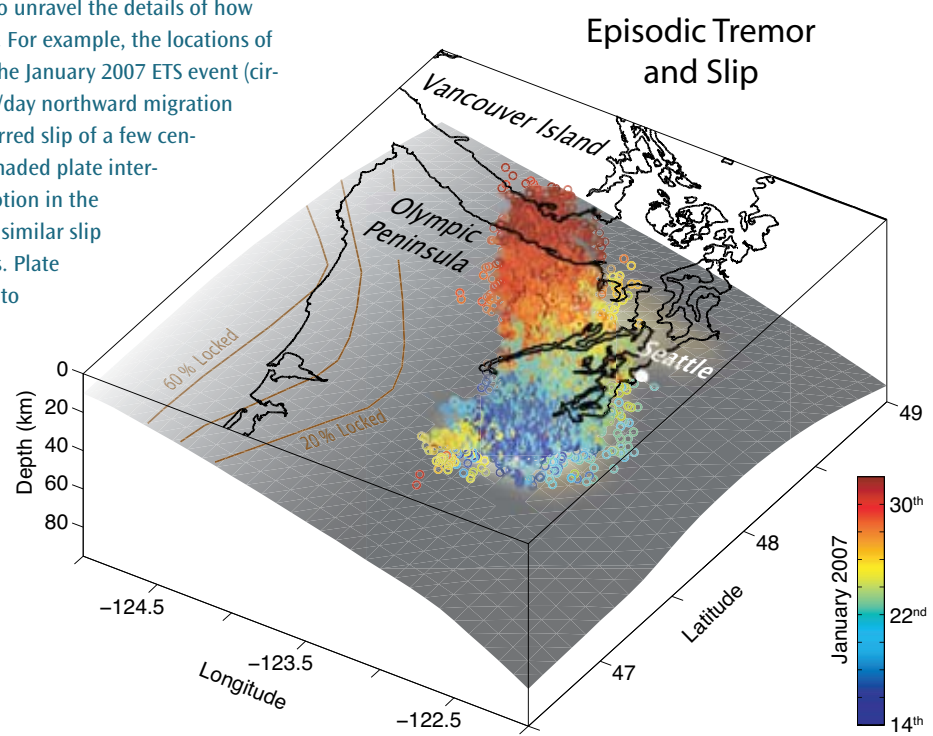
Earthquake Prediction and Predictability

"When will the Big One be?" is the primary question asked of seismologists by the public. Most people asking this question are seeking accurate predictions of earthquake magnitude, location, and time with a high probability of occurrence, such as "there will be a magnitude 7.0 earthquake beneath San Francisco on Wednesday at noon." Confronting the enigma of earthquake prediction has been a challenge to seismology since the emergence of the discipline.

There are two approaches to this problem. The first is the "silver bullet" approach that seeks an unambiguous earthquake precursory signal. The ideal signal would be detectable before all earthquakes. Unfortunately, no such universal precursory signal has yet been identified. There may instead be precursory signals that precede only some earthquakes, and only in specific environments. Candidates include increased seismicity and crustal strain, changes in seismic velocities near a fault, variations in electrical resistivity and potential, radio frequency emission, and changes in ground-water levels and chemistry. These observations are worthy of further research efforts once it has been demonstrated that a specific observation made before an earthquake is unique to the time window before the earthquake. It should be noted that many reported precursory signals have not passed even this basic requirement.

The second approach is to develop an understanding of the complete physical system responsible for earthquakes. Earthquakes involve processes occurring at multiple spatial and temporal scales for which direct observations are severely limited. Much progress has been made understanding crustal deformation, stress accumulation, fault interaction, and rupture dynamics, but the challenge remains to link these processes to the underlying physics of fault rupture. It is also valuable to improve our understanding of patterns of seismicity using high-precision earthquake catalogs that are now being produced by advanced methodologies. Working toward a deterministic understanding of precise earthquake catalogs may reveal many currently hidden aspects of the earthquake system. Studying the basic physical processes of earthquakes and catalogs over longer time periods will reveal whether aspects of the complex earthquake system are intrinsically predictable or not, and what observations may yield the best prospects of providing some predictive capabilities.

The complexity of the earthquake process, and intrinsic observational limitations, may make earthquake rupture a fundamentally unpredictable phenomenon. Even if earthquakes could be predicted with a high degree of probability and accuracy, this would solve only part of society's earthquake problem. The fate of New Orleans after Hurricane Katrina illustrates that even when imminent disaster is predicted several days in advance, there can still be terrible outcomes due to inadequate preparedness prior to an inevitable event. If not built to withstand earthquakes, then homes and livelihoods will still be destroyed. It is thus critical to continue to have a sustained commitment to improving scientifically informed earthquake engineering and mitigation efforts regardless of whether some level of earthquake predictability is ever achieved.

Building devastation from the 2008 Wenchuan earthquake in China.

GRAND CHALLENGE 2. HOW DOES THE NEAR-SURFACE ENVIRONMENT AFFECT NATURAL HAZARDS AND RESOURCES?

A Grand Challenge for seismology is to quantify structures and processes in Earth's near surface environment that affect civilization. Critical problems addressed by seismology involve understanding how seismic waves interact with the near surface to produce strong ground-shaking hazards, evaluating how shallow Earth structure controls the distribution of valuable resources, and determining how the near surface records Earth's history of climate change. These tasks are extremely challenging due to the acute heterogeneity of near-surface Earth structure and associated high seismic attenuation.

The location and severity of most natural hazards is strongly influenced by near-surface materials, whether the ultimate cause of the hazard arises from the Earth, atmosphere-ocean systems, or human activity. Seismic wave sources in the near-surface environment, such as underground explosions, rock bursts, mine bumps, and earthquake faulting, involve significant hazards as well as industrial and political interests. Sediment deposits at or near Earth's surface are the youngest solid Earth structures and therefore record the most recent environmental changes or events (e.g., variability in climate or weather, floods, landslides, and earthquakes).
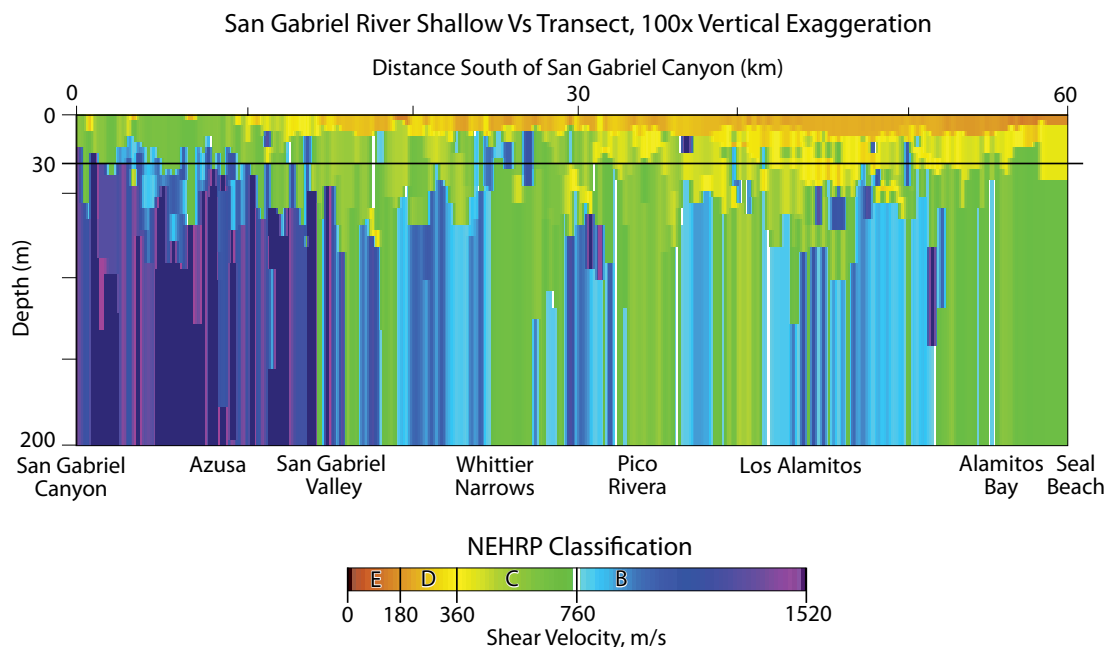
A 60-km long cross section of the upper 200 m of the Los Angeles and San Gabriel basins, at 100X vertical exaggeration, showing measured shear-wave speed. Red-orange regions indicate soils that would strongly amplify ground shaking during an earthquake. The section was derived using seismic surface waves from urban background noise sources. (Image from W.A. Thelen, M. Clark, C.T. Lopez, C. Loughner, H. Park, J.B. Scott, S.B. Smith, B. Greschke, and J.N. Louie, 2006. A transect of 200 shallow shear-velocity profiles across the Los Angeles Basin, *Bulletin of the Seismological Society of America*, 96(3):1055–1067, ©Seismological Society of America.)

Physics-based Prediction of Ground Motions Using Realistic Fault Rupture Models and 3D Geological Structures

Understanding and mitigating earthquake risk depends critically on predicting the intensity of strong ground motion, a daunting scientific challenge. The faulting that generates seismic waves is complex and incompletely understood. Moreover, seismic waves are strongly distorted as they propagate through Earth's heterogeneous crust, which is incompletely mapped. In practice, strong ground motion is characterized using intensity measures, such as peak ground acceleration, or peak ground velocity, in an attempt to capture damage potential. Earthquake engineering relies on parametric relationships that predict the strength of shaking during future earthquakes, based on how the ground motion during past earthquakes varied with factors such as magnitude, distance to fault rupture, and surficial geology.

This empirical approach is adequate for moderate earthquakes; however, there are very few on-scale recordings near large earthquakes, where the hazard is highest. Physics-based strong ground motion simulations have the potential to fill this gap, but only if they accurately reflect the full range of Earth behaviors in the presence of strong seismic waves. Physics-based ground motion simulation is thus an area of intense research and rapid recent progress. An important element of such simulations is dynamic rupture modeling, which considers the joint stress-slip evolution during earthquake shear failure as being driven by the redistribution of stored strain energy and can serve as the foundation for predicting fault behavior and strong ground motion. Dynamic rupture modeling requires the use of today's most powerful supercomputers because representations of faults have to span spatial scales covering many orders of magnitude, and because physical quantities must be calculated at all causally connected points to properly account for stress and slip evolution.
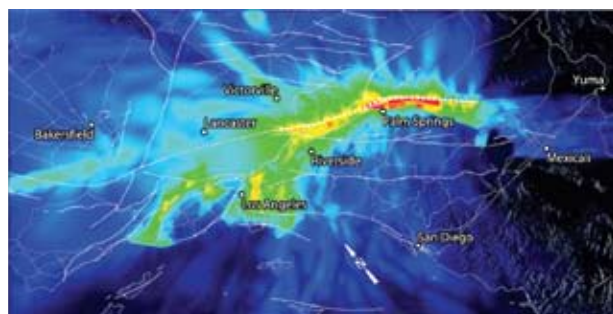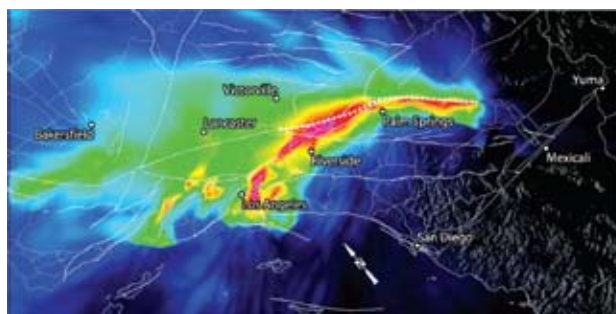
Ground motion intensities (warm colors correspond to high intensities) for a simulated M 7.7 earthquake with SE to NW rupture on a 200-km section of the San Andreas Fault. Strong rupture directivity and intensity amplification occur due to funneling of seismic waves through sedimentary basins south of the San Bernardino and San Gabriel Mountains. The simulation to the left assumes a kinematic (space-time history of slip being prescribed) rupture model, while the one on the right uses a dynamic (physics-based) rupture. The difference in the predicted intensities in this highly populated region underscores the importance of properly characterizing source processes in such simulations. (Image modified from K.B. Olsen, S.M. Day, J.B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. Jordan, 2008. TeraShake2: Spontaneous rupture simulation of Mw 7.7 earthquakes on the Southern San Andreas Fault, *Bulletin of the Seismological Society of America*, 98(3):1162–1185, ©Seismological Society of America)

Near-surface processes affect water, energy, and mineral resources at depths of meters to a few kilometers. Detailed knowledge of Earth's near surface is therefore a crucial part of managing a sustainable environment for civilization.

Near-surface geophysics is undergoing explosive growth because of societal interests in assessing the impact of human activities on our environment. Although the near surface is accessible to drilling and excavation, those activities cannot provide the needed temporal and spatial resolution and must be complemented by near-surface geophysics to "connect the dots." Seismology provides a number of cost-effective and noninvasive near-surface imaging methods, including the use of refracted, reflected, and converted body waves, and surface waves to produce 3D and 4D (time-varying) subsurface maps that have applications for hydrology, civil engineering, earthquake hazard assessment, archeology, nuclear blast detection, and many other critical issues.

Shallow seismic methods play a key role in determining a vast range of geotechnical properties that are critical to the built environment. Depth to bedrock, the load-bearing strength of shallow materials, and the expansive potential of soils can all be estimated from the properties of seismic waves. Seismic studies in conjunction with coring can be used to map lateral changes in specific soil horizons beneath construction sites. The shear modulus of soils is a critical engineering strength parameter for assessing the stability of embankments, buildings, and the foundations of other structures, and it can be quantified by noninvasive seismic shear-wave studies using controlled seismic sources and/or background seismic noise. The extent, thickness, and volume of unstable slopes and past landslides, and mapping weak horizons at their bases, can be used to assess hazards and direct mitigation strategies. Microearthquakes along the sides and bottoms of landslides can potentially be used as a proxy to monitor creep using seismic methods.
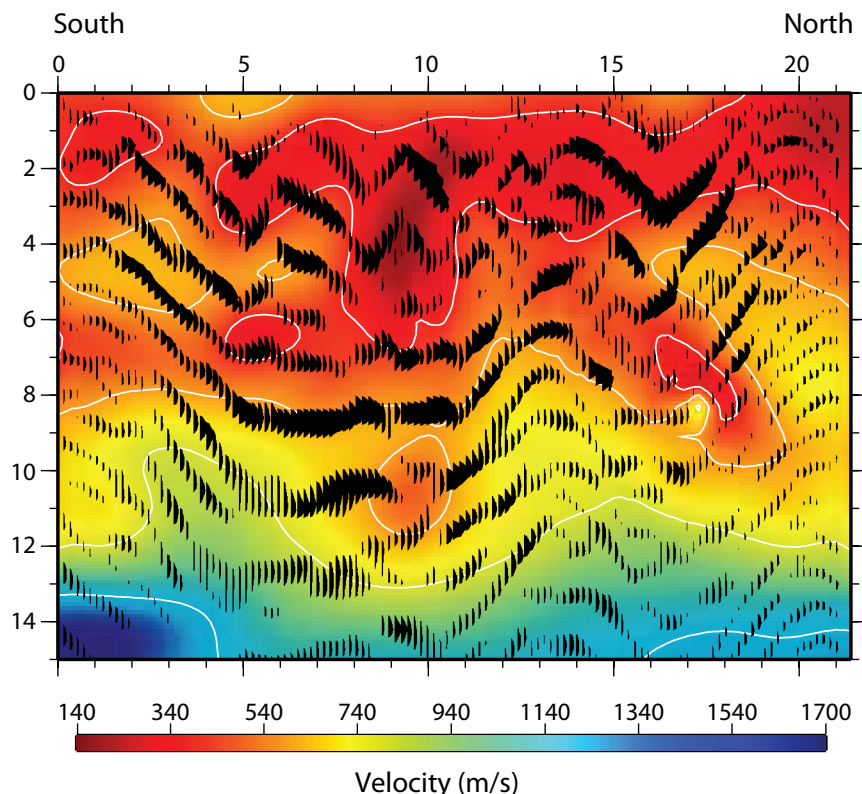
High-resolution (scale in meters) seismic cross section of a subsurface clay-bounded channel containing a dense, nonaqueous phase liquid contaminant. Black lines are the depth-migrated surface seismic reflection data. The reflection data and the red and yellow colors outline the contaminated channel in the center of the image. (Image from F. Gao, A.R. Levander, R.G. Pratt, C.A. Zelt, and G.L. Fradelizio, 2006. Waveform tomography at a groundwater contamination site: VSP-surface data set, *Geophysics*, 71, H1–H11, doi:10.1190/1.2159049.)

Underground Nuclear Explosion Monitoring and Discrimination

Seismology plays a key role in the detection and characterization of nuclear explosions and their discrimination from earthquakes and other types of explosions. Development of the discipline of seismology has been greatly facilitated by the critical geopolitical need to monitor underground nuclear testing conducted at shallow depth in the crust. This mission led to the establishment of the first modern global seismographic network, the World Wide Standardized Seismographic Network (WWSSN), which operated over 100 stations in dozens of nations in the 1960s and 1970s, as well as subsequent global digital seismic networks. The nuclear test monitoring issue has prompted investments in the IRIS/USGS Global Seismographic Network (GSN), the United Nations Comprehensive Test Ban Treaty Organization (CTBTO)

International Monitoring System (IMS), and U.S. Department of Defense monitoring efforts managed by the Air Force Technical Applications Center (AFTAC), along with additional government, academic, and private seismic networks worldwide. Data from many of these efforts (the IMS is an unfortunate notable exception) are openly available in real time via national or regional data centers to facilitate rapid scientific and forensic analysis of anthropogenic and unusual natural events. Operational and basic research in support of nuclear monitoring is carried out by a worldwide contingent of seismologists in universities, national laboratories, and government agencies. These extensive data and research activities have produced advanced capabilities in seismic monitoring, particularly the ability to reliably discriminate signals from small nuclear explosions amidst a background of signals from earthquakes and other natural sources. Whether the CTBT formally enters into force or not, seismology will continue to play a critical role in monitoring of nuclear testing treaties and underground explosion activities worldwide.
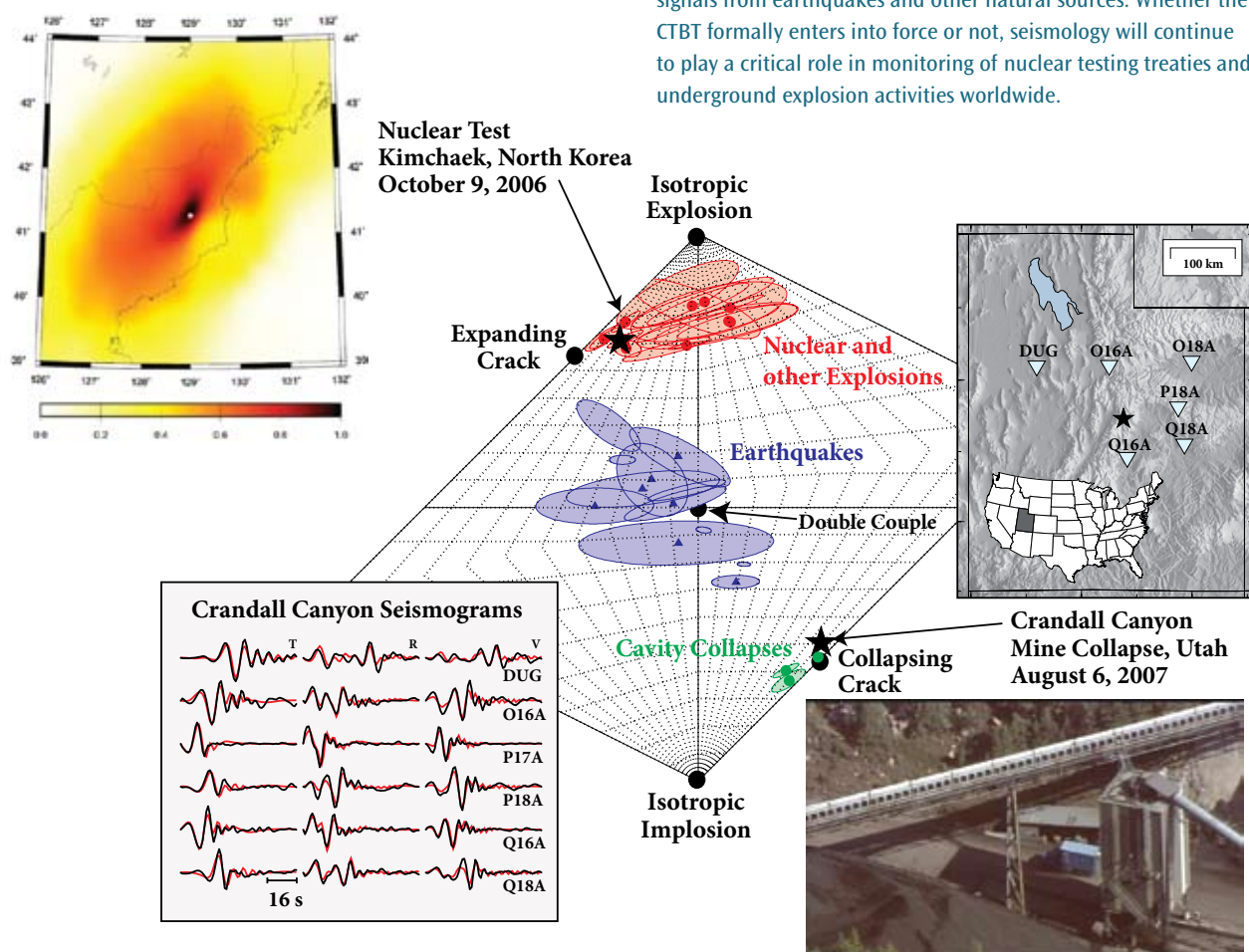
Identifying near-surface seismic sources (discrimination) is a critical problem that has advanced through decades of research and development of both analytical methods and instrumentation. As the discipline has advanced, seismology has achieved robust quantitative discrimination capabilities for various source processes from remote seismic recordings. Most notably, it is possible to distinguish signals generated by underground collapses, earthquakes, and nuclear and other explosions. Shown in the figure are example events mapped according to the relative magnitude of their moment tensor elements (force systems that describe the source type) estimated from seismogram waveform inversions. (Image modified from D.S. Dreger, S.R. Ford, and W.R. Walter, 2008. Source analysis of the Crandall Canyon, Utah, mine collapse, *Science*, 321(5886):217, doi:10.1126/science.1157392. Reprinted with permission from AAAS).

One of the most important challenges for seismology is to understand how strong ground motions are produced by earthquakes, and to translate this understanding into improved National Seismic Hazard Maps that can be directly utilized by the earthquake engineering community. The intensity of earthquake shaking is profoundly influenced, and commonly amplified, by soils and other shallow geologic structures such as basins, resulting in rapidly varying strong ground motions. There can be strong coupling of time-dependent earthquake rupture and seismic wave generation with basin responses, which can be quantified by comprehensive 3D modeling for scenario earthquakes. Characterizing the seismic properties of shallow sedimentary deposits and crustal basins is thus crucial to assessing potential damage during earthquakes.

The potential for soil to liquefy in strong shaking may also be discernible from seismic properties such as shear-wave speed and attenuation, coupled with other geotechnical measurements. Ground rupture and seismic hazard can be predicted by mapping faults at the surface and in the subsurface using seismically imaged offsets in shallow layers. Nonlinear responses of the shallow surface materials to strong shaking can be characterized, along with evaluating the behavior of urban infrastructure embedded in the shallow materials. Improving the models of earthquake occurrence and the complexity of strong ground motions for realistic earthquake ruptures into improved National Seismic Hazard Maps is a critical undertaking that straddles the interface between seismology and earthquake engineering.

Seismic refraction and reflection methods are well-suited to mapping the geometry and bulk mineralogy of shallow rock units, but also can be used to infer porosity and pore-fluid saturation, which are essential for hydrological characterization. In addition to delineating aquifers in sedimentary basins, seismology can be used to map aquifers in fractured rock in regions with more limited groundwater supply.

Compartmentalization or connectivity of reservoirs, dictated by the presence of faults and other structures, is important to predicting how much water may be pumped from a well, and is crucial to maintaining water quality and mapping the flow of natural or human groundwater contamination.

Determining Earth's record of natural climate change relies in part on seismic imaging of shallow sedimentary deposits that record and respond to climate variations. In lake and near shore settings, subtle climate changes alter water levels, biologic activity, and stream sediment, leaving records in the type and thickness of water-bottom deposits. Depositional patterns over large areas are best mapped by seismic reflection, which images boundaries of velocity contrasts. Complementary drilling programs in lake and ocean sediments are generally best designed utilizing stratigraphic patterns mapped in 2D or 3D by seismic reflections. Seismic stratigraphy at the basin scale and on continental margins has long been used to identify sea level changes through time. Such efforts examine, at very high resolution, the shallowest and youngest sediments to constrain climate, typically during the past few hundred thousand years.

Near-surface problems are usually addressed through a combination of shallow geophysical methods and subsurface sampling. Seismic measurements give part of the picture, but incorporation of gravity, electrical, magnetic, radar, and electromagnetic induction data offers improved characterization of the shallow subsurface. An important challenge is joint inversion and interpretation of diverse data for a single consistent subsurface model, including direct identification of sediment, rock, and fluid properties (e.g., porosity and permeability). Such joint inversions are an area of exceptional research promise and presently require careful site-dependent calibration.

KEY QUESTIONS AND ISSUES

- How can the acute heterogeneity in the near surface best be imaged and its material properties constrained in diverse applications?
- How do soils respond to strong ground shaking, and how are nonlinear properties of near-surface materials best calibrated?
- To what extent can seismology resolve permeability and temporal changes in permeability at depth?
- Can physics-based predictions of strong ground motion couple with performance-based engineering to improve seismic hazard mitigation?
- How can the National Seismic Hazard Maps be improved using advanced physics-based understanding of earthquake ruptures and strong ground motions?

- How can time-dependent properties of shallow aquifers best be characterized to monitor water and contaminant transport?
- Can potential ground failures from landslides and karst be robustly assessed and monitored?
- Can nuclear testing be monitored with confidence levels necessary for the Comprehensive Test Ban Treaty?
- What is the resolution of seismological techniques to identify and locate unexploded ordinance, tunnels, buried landfills, and other human-made subsurface hazards?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Develop and broadly disseminate improved 3D wave propagation capabilities for extremely heterogeneous media.
- Develop combined active and passive imaging methodologies using ambient noise.
- Provide dense instrumentation for 4D characterizations of near-source environments.

- Explore cross-disciplinary approaches for quantification of material properties and their nonlinear relationships.
- Increase the number of inexpensive sensors and recording systems to enable multiscale imaging of near-surface environments over large areal extents.
- Add source facilities for high-resolution shallow subsurface mapping in diverse environments.

Gas Hydrates as an Energy Resource, Environmental Hazard, and a Factor in Global Climate Change

At the low temperature and high pressure conditions common in shallow marine sediments and beneath the Arctic permafrost, gas hydrate (an ice-like substance in which molecules of hydrocarbon gases are trapped within cages of water molecules) forms when the gas concentration exceeds saturation. Although estimates of the total mass of methane carbon that resides in this reservoir vary widely, there is general agreement that gas hydrates are common in the sediments on continental margins and must be considered when evaluating the global near-surface carbon budget. In fact, gas hydrates may act as a "carbon capacitor," trapping and storing methane and thus removing it temporarily from the carbon cycle only to release it suddenly as the environmental parameters that control gas hydrate stability change. Research suggests that such abrupt and massive releases of methane from gas hydrates have occurred in the geologic past. A better understanding of how much gas hydrate is present and how it is distributed in seafloor sediments is needed in order to include this effect in global climate models. International research efforts also are underway to evaluate the potential of gas hydrate as a future hydrocarbon source and as an environmental hazard.

Because gas hydrates are not stable at Earth's surface unless the temperature is below $\sim -60^{\circ}$C, remote-sensing techniques are essential for understanding the distribution and dynamics of gas hydrates. The base of the gas hydrate stability zone is often marked by a characteristic seismic reflection, providing an effective tool for large-scale mapping of gas hydrate distribution. High-resolution 3D seismic reflection data image the plumbing system that feeds gas hydrate deposits and are used to guide sampling and long-term monitoring efforts. Waveform modeling can be used to identify local concentrations of gas hydrate. Temporal changes in gas hydrates caused by naturally episodic fluid flow, climate change, or extraction as an energy resource can be monitored through repeated (4D) seismic reflection imaging.
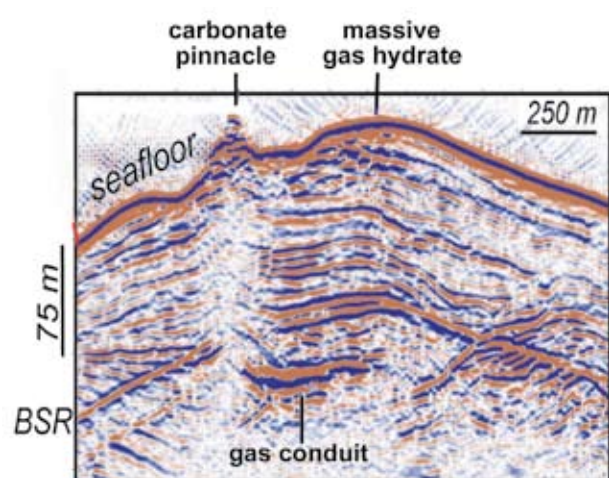
Seismic reflection cross section of the shallow seafloor collected on the continental slope off of Oregon showing a strong bottom-simulating reflector (BSR) marking the base of the gas hydrate layer and the top of free gas in the sediment pore space. The image also shows a carbonate pinnacle chemically deposited by a fluid seep and a subsurface fault that acts as a conduit for upwards gas migration from deeper sources. Photo shows gas hydrate ice. (Images modified from A.M. Tréhu, G. Bohrmann, F.R. Rack, T.S. Collett, D.S. Goldberg, P.E. Long, A.V. Milkov, M. Riedel, P. Schultheiss, and others, 2004. Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: Constraints from ODP Leg 204, *Earth and Planetary Science Letters*, 222(3–4):845–862, doi:10.1016/j.epsl.2004.03.035.)
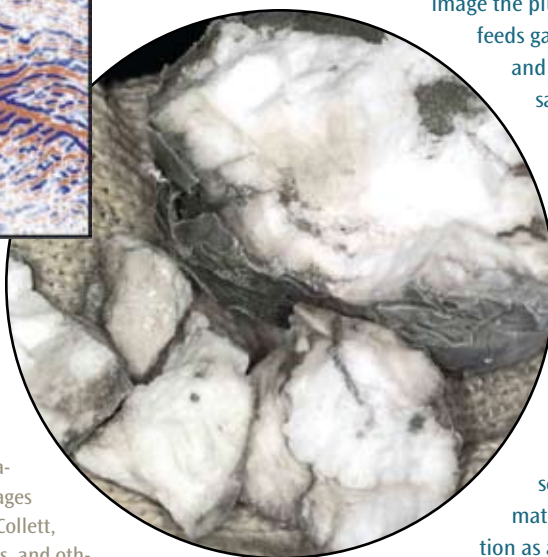
GRAND CHALLENGE 3:
WHAT IS THE RELATIONSHIP BETWEEN STRESS AND STRAIN IN THE LITHOSPHERE?

Plate tectonics provides a context for understanding many large-scale features and phenomena within Earth's relatively rigid crust and outermost mantle (the lithosphere). As a purely kinematic framework, plate tectonics does not quantitatively account for how plates move and deform. Rheology describes the linkage between the forces (stresses) and the resulting deformations (strains) in the rock, and is generally dependent on both temporal and spatial scales (i.e., from seconds for fault rupture during earthquakes, to millions of years for the building of large mountain ranges). Geologic motions and surface strains can now be measured precisely (to resolutions of millimeters) across relevant temporal and spatial scales using large networks of GPS, strainmeter, and tiltmeter instrumentation, but causative stresses can thus far only be approximately inferred. Knowledge of these lithospheric stresses is essential to understanding the forces

a

Plate boundary deformations, involving (a) surface velocities, (b) shear strains, and (c) mean strains, quantified here for the San Andreas system by geodetic measurements, provide a framework for stress accumulation and release, but the overall driving process and resulting earthquake stresses are not well understood. (Image modified from J.P. Platt, B.J.P. Kaus, and T.W. Becker, 2008. The mechanics of continental transforms: An alternative approach with applications to the San Andreas system and the tectonics of California, *Earth and Planetary Science Letters*, 274:380–391, doi:10.1016/j.epsl.2008.07.052.)

b

c

Remote Earthquake Triggering by the Denali Earthquake

Seismic waves from the 2002, M_w 7.9 Denali, Alaska, earthquake triggered earthquakes thousands of kilometers away, particularly along the southeasterly direction of fault rupture towards which the amplitudes of seismic waves were enhanced. As the waves spread past Bozeman, Montana, 3000 km from the source faulting, they stressed local faults, causing them to fail in the form of tiny earthquakes. Signals from these local earthquakes (indicated by arrows in the middle panel) are apparent when the much-lower-frequency waves from the Denali event are removed from the seismogram by filtering. A closer look at one of these small events (lower panel) confirms that they are indeed from local earthquakes triggered by the Denali event waves. The reason why these local earthquakes persist long after the Denali seismic waves have passed remains an unsolved mystery. These data provide a means of determining the stress changes that drive frictional instabilities of earthquake faulting. (Image courtesy of M. Manga and E. Brodsky.)
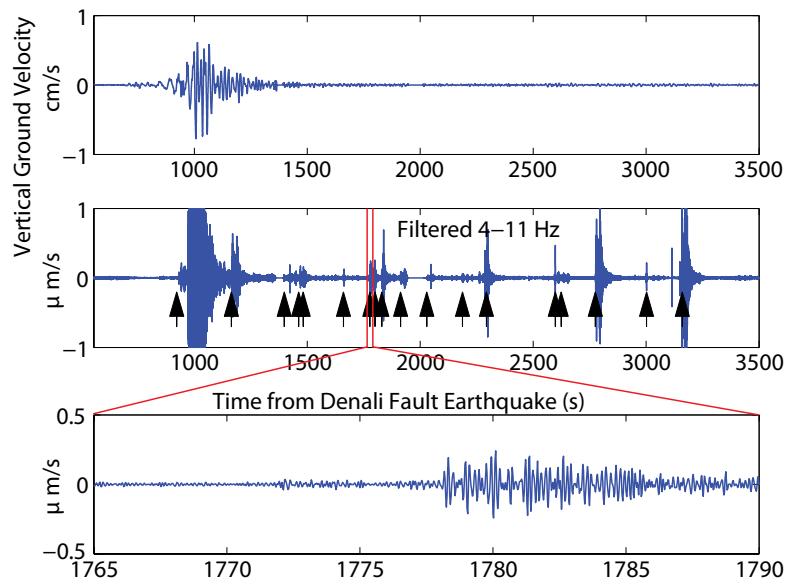
driving deformation at plate boundaries and within plates, and localized redistribution of stress accompanying the earthquake cycle. Seismology, along with geodesy and other geoscience disciplines, plays a fundamental role in the Grand Challenge of quantifying the stress distribution, rheology, and thermodynamic properties of materials in the lithosphere.

Aftershocks provide the most general example of interacting earthquakes; changes in Earth's static stress field surrounding the source region of a major earthquake can be related to aftershock occurrence. In addition, since the 1992 Landers earthquake, it has been clear that seismic waves from one event can trigger other earthquakes at much greater distances (up to tens of thousands of kilometers) than is possible with static stress changes. These local and remote triggering phenomena reveal important attributes of stress in the Earth and their relationship to earthquake occurrence, given that changes in stress caused by seismic

waves and faulting can be quantified. Relationships between aftershocks and slow deformations associated with post-earthquake re-equilibration from GPS and strainmeter observations can be used to resolve rheology and stress transfer mechanisms.

Many of the limitations on what can be learned from our seismic and geodetic data, imposed by the slow pace of geologic processes and the relatively short time of observation, may be partially overcome using computer simulations of the behavior of complex, interacting fault networks embedded in ever-more realistic Earth models. Earthquake sequence simulations spanning many thousands of earthquake cycles incorporate the latest in "petascale" computing, to address how stress redistributes as fault systems evolve.

Seismic approaches can constrain diverse properties of lithospheric structure, such as the depth and topography of the Moho (the discontinuity between

the crust and mantle), 3D rigidity of the lithosphere, and identification of the brittle/ductile transition separating regions of stick-slip faulting from fault creep. These models, combined with topographic and gravity data, can be used to estimate lithospheric stress and to assess the relative contributions between internal forces and plate boundary forces.

Anisotropy is an imprinted directionality in the structural and/or mineral fabric that causes seismic shear waves with different shaking directions to travel with different speeds. The analysis of modern three-component digital seismograms can separate these different parts of the seismic wavefield to provide measures of anisotropy and constraints on the long-term history of strain in the lithosphere. Anisotropy measurements permit estimation of the magnitude and orientation of shear strain in the ductile sublithospheric mantle (the asthenosphere) and consequent inferences about the orientation of the shear stress at the base of the lithosphere. In many cases, seismically measured mantle anisotropy is used as a proxy for flow or deformation. These studies offer unique constraints on how flow affects plate motion and the transfer of stress to and within the lithosphere.

KEY QUESTIONS AND ISSUES

- What is the state of stress on active faults and how does it vary in space and time?
- What are the stress-strain laws of faults and the surrounding crust that give rise to slow and fast slip?
- How do pore fluids influence the stress environment in fault zones?
- What is the relative importance of static (elastic) versus dynamic (vibrational) stress changes for earthquake triggering?

- What is the time-dependent rheology (material response to forces) and its variability throughout the crust and mantle?
- How are new faults initiated and reactivated throughout Earth history?
- Are observed statistical characteristics of earthquakes caused by material or geometric heterogeneity or by nonlinear dynamics?
- Can we develop general models of strain accumulation and release consistent with geodesy, paleoseismology, landform evolution, and laboratory constraints on rheology?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Perform rapid post-event drilling into fault zones guided by 3D seismic imaging to quantify frictional heating and conduct time-dependent hydro-fracture measurements to quantify in situ stresses.
- Deploy new offshore ocean bottom seismometers (OBS), pressure sensors, and seafloor geodetic instruments to understand submarine earthquake cycles.

- Increase coordination between different disciplines making stress and differential stress measurements.
- Determine changes in fault slip directions over time and model relative to absolute stresses.
- Develop robust anisotropic models for the lithosphere.

Seismology and Probabilistic Hazard for Waste Repository Siting

National Seismic Hazard Maps (http://earthquake.usgs.gov/hazmaps/) provide a probabilistic assessment of strong ground motions for any location across the United States and drive the design criteria for new construction. The catastrophic nature of structural failure at critical facilities, such as nuclear power plants and long-term waste repositories, requires construction to even higher standards of ground-shaking tolerance, as would be generated by large events with very small probabilities of occurrence. Historic records only document recent earthquake activity, even when supplemented with mapping and trenching of fault zones, and may not include the largest possible events in any given region. It is thus necessary to extrapolate hazard curves to estimate ground accelerations and velocities to levels that have never been historically recorded. Advances in our understanding of the physics of earthquake rupture, combined with massive computational capabilities, allow exploration of the range of physically plausible ground motions. The challenges include generating reasonable slip time histories and accounting for the very small-scale, near-surface structure. Model validation and verification requires multiple modeling approaches and additional model constraints, respectively. Validation of numerical codes uses some of the largest computing facilities currently available. The search for constraints on prehistoric ground motion is also underway. For example, precariously balanced rocks, precipitous cliffs, and fragile geological formations can be used to set bounds on ground motions experienced over geologic time scales.
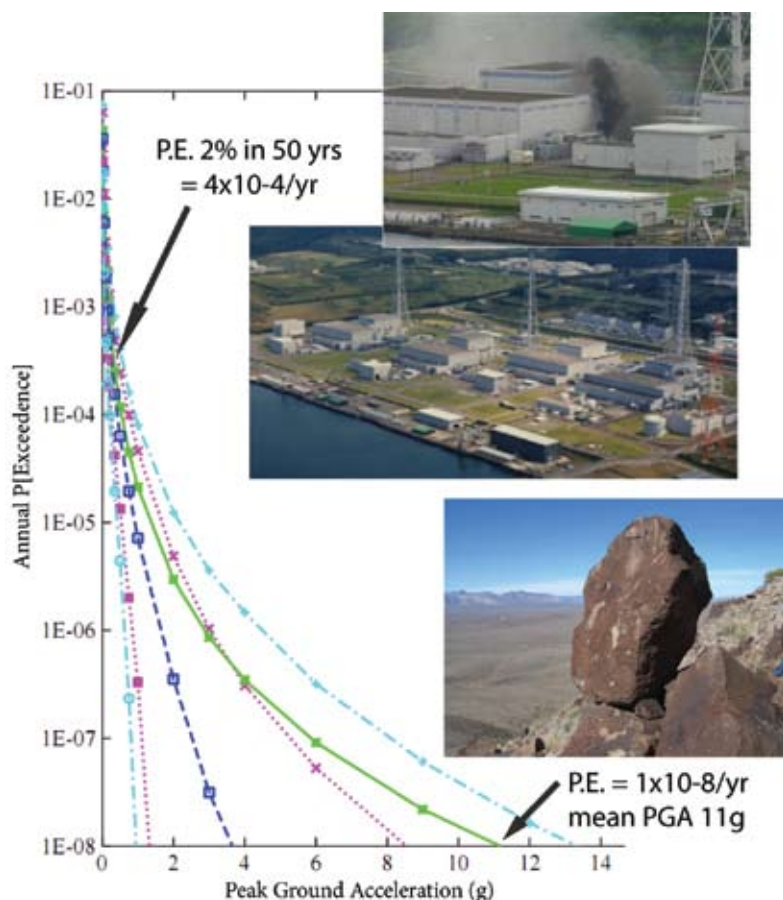
Probabilistic seismic hazard curve for Yucca Mountain, Nevada, showing peak ground acceleration (PGA) plotted against the annual probability of exceedance (P.E.). Most buildings are designed to withstand shaking with a P.E. of around 10% in 50 years and life-safety designs (avoiding catastrophic building collapse) are for a P.E. of around 2% in 50 years. The design criterion for the proposed long-term nuclear waste repository at Yucca Mountain is 1×10^{-8}/yr (Plot from J.S. Stepp and I.G. Wong, 2003. Probabilistic seismic hazard analysis for Yucca Mountain, Presentation to the Nuclear Waste Technical Review Board, February 24, 2003.) Photos: Balanced rocks can be used to constrain limits on peak ground motions observed over geological time scales (bottom). The Kashiwazaki-Kariwa Nuclear Power Plant in Japan (top and middle) was damaged during the July 16, 2007, Mw 6.6 Chuetsu earthquake. A transformer at the site caught fire and leaked fluids and gases. The ground motion in this earthquake exceeded the design criteria and the reactor, Japan's largest, is presently closed. (Top photo by Japanese Coast Guard via Bloomberg News. Middle photo by Tokyo Electric Power Company from World Nuclear Association Picture Library. Bottom photo courtesy of M. Purvance.)

GRAND CHALLENGE 4. HOW DO PROCESSES IN THE OCEAN AND ATMOSPHERE INTERACT WITH THE SOLID EARTH?

Seismology readily detects signals from natural sources such as ocean storms, bolides, tornados, and glacier calving. A new era of research has recently opened up at the interface of solid Earth geophysics, glaciology, oceanography, and atmospheric science, with high potential for transformative science and societal relevance. This multidisciplinary topic of how processes in the ocean and atmosphere couple into seismic waves in the solid Earth and how these can be used to monitor the global environment is one of the high-priority Seismological Grand Challenges.

There is great interest in understanding the coupling mechanisms between ocean waves and seismic waves over broad frequency ranges because it enables seismic monitoring of ocean processes and, in turn, the coupling of oceanic and atmospheric energy into the solid Earth provides a novel source for exploring Earth's interior. Earth's long-period "hum," or continuous excitation of the planet's free oscillations at periods of hundreds of seconds, was discovered just ten years ago in high-quality continuous records from the Global Seismographic Network (GSN) accumulated
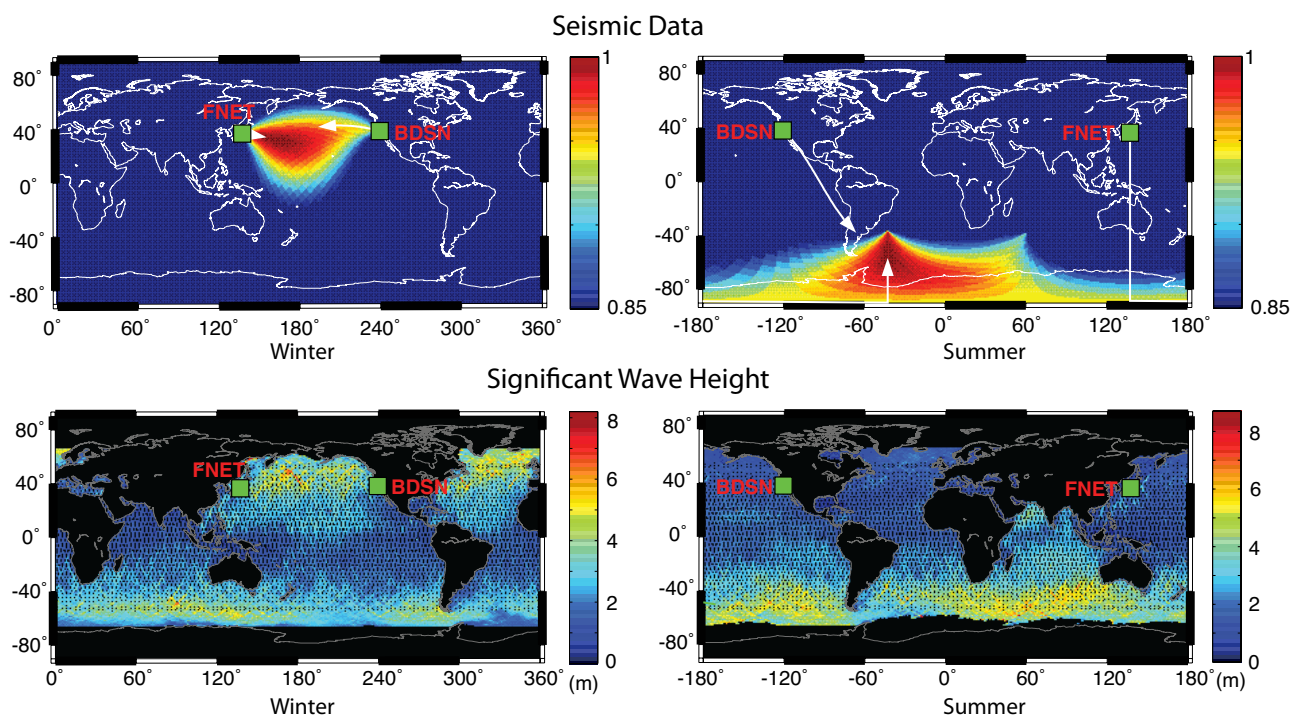
Comparison of seasonal variations in the distribution of long period "hum" sources (top) from array analysis using very broadband seismograph (STS-1) recordings, and significant wave height in the oceans (bottom) from satellite observations. Hum sources (the color bar indicates areas generating hum with amplitudes larger than 85% of the maximum) track the location of the strongest winter storms. Top left: averages for the winter months (January to March and October to December). Top right: averages for the summer months (April to September). Bottom: averaged images from Topex/Poseidon for the month of January (left) and July (right). (Reprinted by permission from Macmillan Publishers Ltd: J. Rhie and B. Romanowicz, 2004. Excitation of Earth's incessant free oscillations by atmosphere-ocean-seafloor coupling, *Nature*, 431:552–556, doi:10.1038/nature02942, ©2004.)
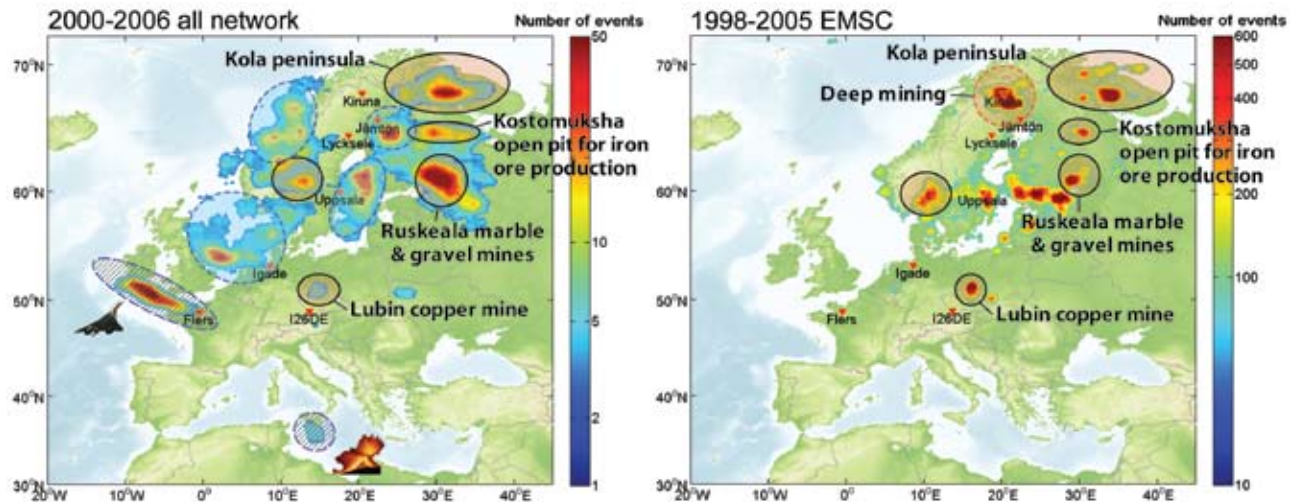
Left: Infrasonic sources monitored across Europe using regional infrasound records for 2000–2007. Right: non-earthquake events reported in seismic catalogs for the overlapping period 1998–2005. Major mining regions are circled, and clearly have both seismic and infrasonic sources. (Image modified from A. Le Pichon, J. Vergoz, P. Herry, and L. Ceranna, 2008. Analyzing the detection capability of infrasound arrays in Central Europe, *Journal of Geophysical Research*, 113, D12115, doi:10.1029/2007JD009509.)

over several decades. It has now been established that the primary sources of the hum are related to mid-latitude winter storms generating strong ocean waves that couple to the ocean floor via nonlinear mechanisms that are still poorly understood.

The ocean wave origin of the shorter-period "microseism" (between about 4 and 30 s) background was demonstrated in the 1950s, but for decades this ubiquitous signal was widely treated as troublesome noise. In fact, the microseism is a unique global integrator of storm energy spanning the world's ocean. Seismologists and collaborators are now working to elucidate the relationship between Earth's seismic background excitation across hum and microseism periods to ocean wave and atmospheric processes. This research is of interest to a large, multidisciplinary community, with applications ranging from the study of Earth structure, to effects on floating sea ice, to coastal oceanography (e.g., the effects of long-period ocean waves [infragravity waves] in harbors).

Seismology is providing a new and valuable integrative window into climate change at scales not otherwise accessible. Global warming affects broad-scale atmospheric circulation patterns, resulting in changes to storm duration and intensity. The microseismic and hum noise both track large ocean storms and their wave interactions with coastlines. Monitoring changes in wave activity and identifying whether changes have occurred in the wave system over the past century, especially in the southern ocean, may be reliably determined from archived seismograms from stations near the coast. It was also recently discovered that seismic methods can detect layering and mixing in the water column itself. Images with unprecedented horizontal resolution of oceanic structure can be used to derive quantitative estimates of internal wave energy and turbulent mixing that can help illuminate thermohaline circulation, which plays a key role in climate and natural sequestration of atmospheric carbon.

Seismologists and glaciologists are now collaborating in efforts to track how polar ice sheets are affected by global warming. Glacial earthquakes, resulting from the sudden (tens of seconds) movement of very large volumes (cubic kilometers) of ice, largely escaped attention until recently because they do not generate the short period (1–10 s) seismic waves visible at large distances that are used for standard earthquake

detection and location algorithms. Glacial sources that involve floating ice systems, such as calving, excite tsunami-like ocean waves that can be detected with seismometers deployed both on land and on floating ice, and offer additional new opportunities for monitoring key processes associated with the stability of tidewater glaciers and ice shelves.

Seismic sources within the solid Earth generate waves that propagate not only through the ground but also through the ocean (e.g., tsunami and T-phases), atmosphere (e.g., infrasound generated by volcanic eruptions and earthquakes), and even the ionosphere, where remote sensing using GPS and radar technologies hold potential for new ways to characterize the sources of large earthquakes. An explosion or disturbance near Earth's surface produces both seismic and infrasound energy, the latter being best observed on

microbarographs or, at high frequencies, by microphones. Atmospheric phenomena including tornados, meteorite impacts, and lightning strikes can be monitored by collocated seismic and infrasound sensors, providing new constraints on these processes and their global occurrence. It may also be viable to combine seismic and infrasound monitoring to detect and quantify wildfires using similar strategies to those used for volcanic eruptions. Seismic recordings can also sense changes in atmospheric pressure that causes ground tilt such as the rare "Morning Glory" cloud formations observed in Los Angeles and Australia. Combining seismic and infrasound recordings can help elucidate the way in which sound waves propagate through the atmosphere, and therefore provide a better understanding of atmospheric structure and its variation with time at spatial and temporal scales inaccessible by other means.

Cryoseismology

Cryoseismic research involves quantitative studies of ice processes that in many cases are known or suspected to show sensitivity to climate change. For example, high-quality seismographic networks can be deployed to study ice shelf stability/disintegration, which has been discovered to sometimes occur catastrophically. Recent research topics also include tectonic evolution of west Antarctica and the history of ice cap changes; studies of tidally modulated stick-slip motion of ice streams in west Antarctica; seismic and ocean acoustic observations of the collisions and break-up of Earth's largest ice shelves and ice bergs; remote detection of glacial calving via sea swell "mini-tsunamis" using broadband seismometers deployed atop giant tabular icebergs, and study of a newly observed class of remotely detectable slow glacial earthquakes from major tidewater outlet glaciers in Greenland. In each application, seismology can uniquely contribute to the quantification of the sources and structures involved in the dynamic polar environments.
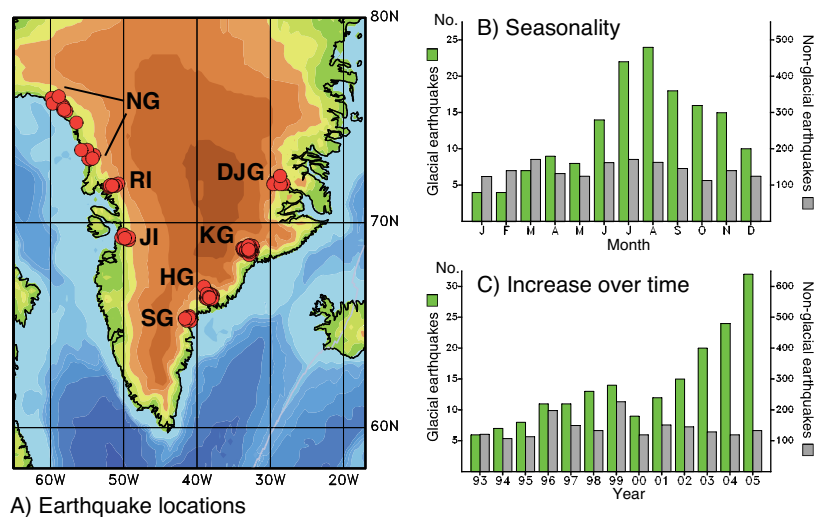
Example of novel glaciological signals studied with seismology. Seismically identified and located long-period glacial events detected with the GSN are associated with major outlet glaciers in Greenland, showing seasonality and annual variability. (Image from G. Ekström, M. Nettles and V.C. Tsai, 2006. Seasonality and increasing frequency of Greenland glacial earthquakes, *Science,* 311(5768):1756–1758, doi:10.1126/science.1122112. Reprinted with permission from AAAS.)

Seismic Imaging of Ocean Structure

During routine seismic profiling of subseafloor structure off the Grand Banks on R/V *Ewing*, data collected to reveal structure within the sediments was found to also resolve variations in water temperature and salinity within the ocean itself. Thermohaline fine structure is usually mapped by lowering and raising instruments that measure water properties directly, but this slow process limits the volume of ocean that can be sampled and has constrained horizontal resolution. By tuning the processing of the seismic reflection records to emphasize ocean structure, boundaries between water masses can be rapidly mapped, revealing layers as thin as 5 m with unprecedented lateral resolution. The deeper, rounded structures in this image represent kilometer-scale eddies that are thought to play a major role in mixing within the water column. Seismic reflection techniques provide an ideal complement to traditional methods of probing the ocean, offering a way to rapidly illuminate large volumes,
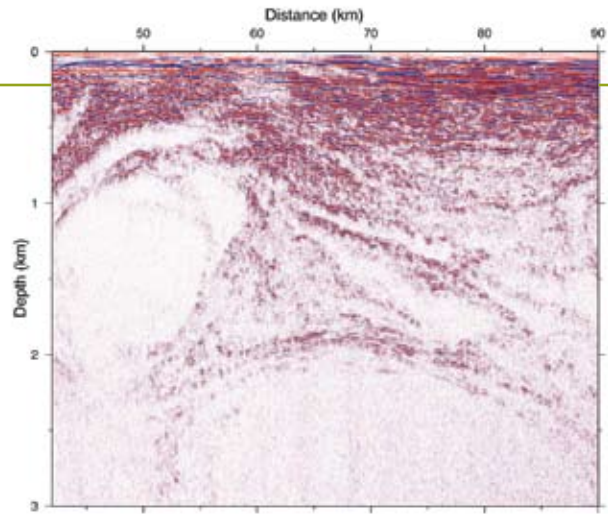
thus providing the possibility of 3D and 4D (time-lapse) imaging of the complex oceanic structures involved in oceanic mixing and transport. (Image courtesy of S. Holbrook.)

KEY QUESTIONS AND ISSUES

- How are Earth's normal modes excited by phenomena in the atmosphere and ocean?
- How do ocean wave and other seismic background noise variations track climate change?
- Are models of thermohaline circulation consistent with seismic images of oceanic internal structure?
- How can seismic and infrasound data best be used to study tornadic storm systems and tornado touch downs?

- How can bounds be placed on the energy budgets and other physical properties of bolide impacts, glacial calving, volcanic eruptions, and other sources jointly observed by seismic and atmospheric monitoring?
- What conditions lead to ice-shelf collapse and can we monitor them in advance?
- What is the nature of friction and the role of fluids at the base of glaciers?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Sustain global and continuous observations of very broadband seismic signals on land and on the seafloor to evaluate mechanisms of hum and microseism excitation, coupled with wave height measurements with improved resolution in time and space.
- Increase the number of collocated infrasound and seismic stations.
- Make more hydroacoustic and infrasound data sources openly available for basic research.
- Develop an authoritative catalog and methodology for estimating size, duration, and other physical properties of non-earthquake seismic events.

- Install greater numbers of permanent broadband seismic networks in polar regions for long-term observations.
- Acquire large numbers of low-temperature-capable portable broadband seismic and geodetic instruments for temporary deployments in polar regions for experiments around ice-shelves, glacial streams, near glacier outlets, and in other cryospheric systems.

GRAND CHALLENGE 5.
WHERE ARE WATER AND HYDROCARBONS HIDDEN BENEATH THE SURFACE?

Fluids in Earth's interior can be detected by seismic waves because there are large contrasts in wave properties between fluids and solids. Spatial and temporal variations in the distribution of water and hydrocarbons are primary targets for high-resolution seismic imaging of the shallow Earth. Water and other volatiles also play major roles in controlling material rheology and magma production within the deeper Earth. Thus, mapping and monitoring changes in the distribution and circulation of fluids and volatiles in Earth's interior is one of the key Seismological Grand Challenges.

Water is of fundamental importance to the evolution of the Earth, the only "water planet" in our solar system. Water affects the evolution of the continental and oceanic lithosphere by transferring geothermal heat during hydrothermal circulation. Water in pores and cracks weakens faults by reducing the effective pressure on the fault surface, it reacts with rocks to form minerals such as talc that further lubricate fault slip, and dissolved water in the mantle lowers viscosity of the asthenosphere, facilitating convection; indeed, it is widely accepted that these effects are necessary for plate tectonics. Carbon dioxide and water are fundamental drivers of explosive volcanic eruptions and these dissolved gases lower the melting temperature needed for magma production. Water-filled cracks contribute significantly to the attenuation of seismic energy in the Earth, as can be clearly seen by comparison with the persistence of scattered energy on seismograms from the dry lunar crust. Fully developing and exploiting geothermal energy requires high-resolution knowledge of crustal structure and fluid distributions.

Water is carried back into the mantle by subduction. Although the amount at depth, particularly greater than about 400 km, is still unknown, it is likely that the mantle accommodates the water equivalent of several global oceans. It has recently been proposed that mantle upwelling and mantle mineralogical phase transitions produce large regions of concentrated hydration and partial melt near the global discontinuity at a depth of 410 km in the mantle. Understanding effects of water on ongoing mantle processes and Earth evolution has spawned scientifically rich multidisciplinary observational and theoretical efforts employing seismology, mineralogy, geodynamics, petrology, and rock mechanics.

Civilization is utterly dependent on access to fresh water from surface sources and from near-surface aquifers. Ninety-five percent of this accessible liquid fresh water is stored as groundwater (the vast majority of near-surface water is either ocean salt water or glacial ice). The recharge, flow, and storage of groundwater are heavily influenced by geologic stratigraphy and fault distribution. The principal imaging of these critically important subsurface structures is through seismology, which also offers the ability to estimate the volume of water stored within cracks and pores.

The formation, migration, and storage of Earth's liquid and gas hydrocarbons, as well as geothermal energy reserves, are similarly constrained by geological structures. Because of its unique ability to resolve subsurface detail, seismology is thus not only key to surveying and assessing the large basins that hold most of the world's usable groundwater, but is also the cornerstone of the global hydrocarbon exploration, production,

Exploration Seismology and Resources: Energy and Mining

Seismic reflection methods are the medical ultrasound of "mother" Earth. They produce the highest-resolution images of the subsurface, and have been adopted globally by industry as an essential and cost-effective method of finding, developing, extracting, and managing energy, mineral, and groundwater resources. Industry enthusiastically adopted 3D seismic reflection imaging more than 20 years ago to image structural and reservoir complexity, and more recently has developed 4D, or time-lapse repeat surveys, to monitor reservoir mechanical and fluid changes during resource extraction. This is increasingly accompanied by monitoring of production-induced microearthquake activity. Three-dimensional seismic reflection has enjoyed moderate usage in the coal industry, especially to delineate coal-bed methane deposits, and is likely to grow as easily accessible deposits are exhausted. Seismology is less commonly used in mineral exploration and development, but has great potential for growth; pioneering work outside of the United States has proven valuable in mapping mineral deposits. Challenges exist in adapting the petroleum industry tools to nonlayered and steeply dipping targets in crystalline rocks. Seismic imaging has also been used to track mining-induced stress changes in the rocks that lead to "mine bumps," induced earthquakes, and cavern collapses, and plays a key role in mining safety measures. Similar coupled imaging and microearthquake monitoring holds great potential for geothermal energy exploration and production.

The petroleum industry relies on high-resolution seismic surveying to map oil and gas reservoirs at depths of up to 7 km. Though costly, 3D seismics yield the detail necessary to image the faults and complex sedimentary features that can trap energy reserves. This 3D "sonogram" traces the origin and properties of rock layers and reveals the most likely targets for drilling and extraction. Using 3D seismic imaging, industry has cut the number of nonproducing "dry" holes by more than half since 1990. (Ship image from B. Dragoset, 2005. *The Leading Edge*, 24:S46–S71, and Western Geophysical. "F3" seismic data and analysis from F. Aminzadeh, and P. de Groot, 2006, *Neural Networks and Other Soft Computing Techniques with Applications in the Oil Industry*, EAGE Book Series, ISBN 90-73781-50-7. Visualization by J. Louie.)
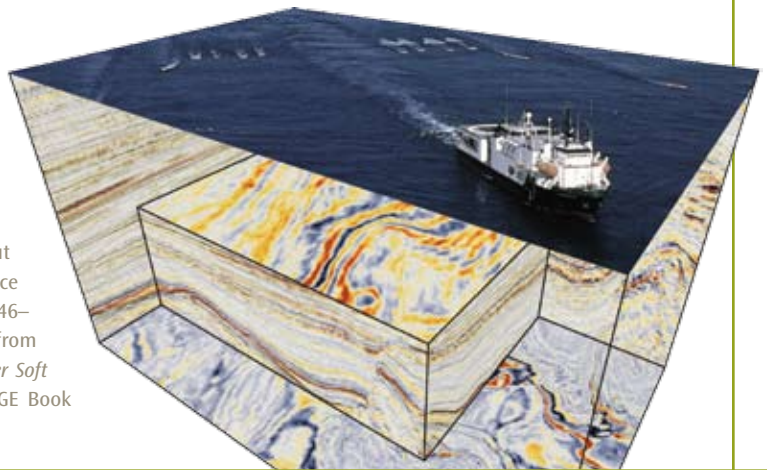
and reservoir management industry. Seismological techniques, including 4D (time-lapse) mapping, are increasingly used to monitor the extraction and movement of hydrocarbons and water in producing fields in real time. Seismic exploration and production on land and at sea is a multibillion dollar industry with major workforce needs now and in the future.

Resources are currently being extensively applied worldwide to investigate geological reservoirs for their carbon dioxide sequestration potential. Methodologies for managing such sequestration efforts will rely critically on seismology, both to monitor spatial and temporal changes in seismic velocities corresponding to the fluid content, and to detect brittle-failure-induced microearthquakes generated by the injection process. Such methodologies are already in place in numerous producing hydrocarbon fields to monitor production and are readily adaptable to carbon sequestration applications.

KEY QUESTIONS AND ISSUES

• How can we improve the detection, characterization, and production of hydrocarbon resources, including detecting deep deposits beneath salt, finding small-scale pockets in incompletely extracted reservoirs, and monitoring porosity, permeability, and fluid flow at high resolution?

Seismology Workforce Issues

The national need for well-trained geoscientists, including geophysicists and seismologists is well documented by the U.S. Department of Labor, the U.S. Department of Education, and the American Geological Institute. The current geoscience workforce is aging, with the majority being within 15 years of retirement age. The current percentage of geoscientists between 31–35 years old is less than half that of geoscientists between 51–55 years old and there are not enough students being produced to fill the positions that will be vacated by retirements. By 2020, the current U.S. workforce, plus new U.S. entries, is estimated to fall short of the projected geoscientist demand from the petroleum industry alone by 20,000 jobs. The Bureau of Labor Statistics estimates an employment growth of 22% for geoscientists between 2006 and 2016, much faster than the average for all occupations. The need for energy, environmental protection, and responsible land and water management is expected to further spur employment demand.

Geoscience PhDs are particularly needed for teaching and training the next generation of students, and for performing basic research. The "Digest of Educational Statistics" documents the low number of geological sciences PhDs (505 in AY 2005–2006). Digest statistics show a high percentage of PhDs being awarded to nonresident aliens in physical Sciences (44% in 2005–2006, an increasing percentage of which are returning to their home countries), and low participation rates by women (30% of the 2005–2006 PhDs), and underrepresented minorities (4%).

Addressing the geoscience workforce issue requires attention at the K–12 level, where U.S. students are lagging in science and mathematics training relative to international peers. Efforts are needed to alert entering university student to the excitement and career potential for geoscience majors. A number of summer internship programs for undergraduates have been successful in promoting advanced study and careers in seismology. The NSF research experiences for undergraduates (REU) program has promoted internships associated with NSF-funded projects. Summer internships include those sponsored by IRIS, SCEC, and the UCAR/UNAVCO SOARS/RESESS program. Summer camps such as SAGE provide technical training in applied geophysics in the field. These internships provide experiences that contribute to many students' decisions to pursue graduate work in seismology and geophysics.

These efforts need to be sustained and expanded, and concerted efforts need to address the pipelines that bring students into seismology and other geoscience disciplines.

IRIS summer intern Justin Brown servicing a seismograph station in the Valley of Ten Thousand Smokes of Katmai National Park, Alaska, in 2004. (Image courtesy of IRIS; photo by J. Cundiff.)

IRIS summer interns work with university faculty and graduate students to collect reflection data during the IRIS intern program orientation week at New Mexico Tech. (Image courtesy of J. Taber.)

- How can we efficiently and inexpensively quantify and monitor extraction and replenishment of groundwater resources using seismological techniques?
- What is the potential for sequestration of large volumes of carbon dioxide in underground reservoirs?
- How can we image fracture systems, including fracture orientation and density, and presence of fluids, and time-dependent changes in these systems?

- To what extent does water control slip on faults?
- How much water is stored in the transition zone of the upper mantle? How much water is transported into the lower mantle?
- Does dissolved water contribute significantly to the low viscosity of the asthenosphere?
- To what extent is global mantle convection facilitated by the presence of water?
- At what depth, by what processes, and to what extent are subducting slabs dehydrated?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Improve computational modeling of wave propagation in complex media, including attenuation, anisotropy, and nonlinear effects.
- Expand use of repeated, high-resolution 3D active surveys to yield 4D monitoring.
- Improve techniques for using seismic noise for continuous monitoring of reservoir systems.

- Tomographically image the mantle and crust at higher-resolution.
- Develop methods for joint interpretation of seismic, electromagnetic and gravity observations.
- Increase collaborations among seismologists, geodynamicists, geochemists, hydrologists, petrologists, and electromagnetic geophysicists.
- Expand the educated workforce, especially for industry.

Four-Dimensional Imaging of Carbon Sequestration

High-resolution subsurface imaging provides models of 3D structures at depth, which include fluids, impermeable rock layers, and subsurface geologic structures. Repeated imaging detects time-dependent changes in the subsurface conditions, including those resulting from fluid extraction, fluid injection, and reservoir compaction. In carbon sequestration, where CO_2 is injected into deep rock layers to isolate it from the atmosphere, it is critical to assess where the gas goes and how effectively it is contained. Seismology offers key information for identifying viable structures for sequestration, and for 4D monitoring of injection and migration. A practical example of this is shown above for the CO_2 injection at Statoil's Sleipner field in the Norwegian North Sea, which has had more than 8 Mt of CO_2 injected into the reservoir. Time-varying reflection images are differenced to determine how the CO_2 has distributed in plumes throughout the medium. This method ensures the integrity and maximal utilization of the sequestration reservoir. (Image from R.A. Chadwick, R. Arts, and O. Eiken, 2005. 4D seismic quantification of a growing CO_2 plume at Sleipner North Sea, Pp. 1385–1399 in *Petroleum Geology:*

North-West Europe and Global Perspectives: Proceedings of the 6th Petroleum Geology Conference, A.G. Dore and B.A. Vining, eds., Geological Society, London.)
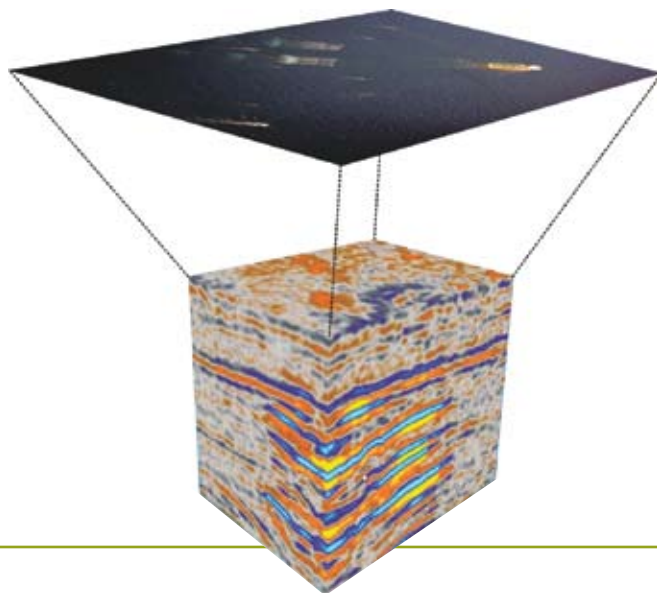
GRAND CHALLENGE 6.
HOW DO MAGMAS ASCEND AND ERUPT?

Volcanic eruptions are spectacular and often danger-ous geological events that threaten hundreds of mil-lions of people worldwide. Large explosive eruptions can scatter ash over hundreds of kilometers and can inject ash into the stratosphere that alters global cli-mate for years. Lesser eruptions can introduce ash at elevations that seriously threatens airline traffic. Lahars (volcanic mudflows) can race down valleys, wiping out settlements tens of kilometers away from the erup-tion. Lava flows can gradually or suddenly alter the landscape, covering up human-made structures along the way. Poisonous gases that are emitted can be silent killers. Seismology provides probes of volcanic pro-cesses occurring both at the surface and in Earth's deep interior, which places it at the forefront of inves-tigating the distribution and dynamics of melting and eruption of magmas. Quantifying the presence and
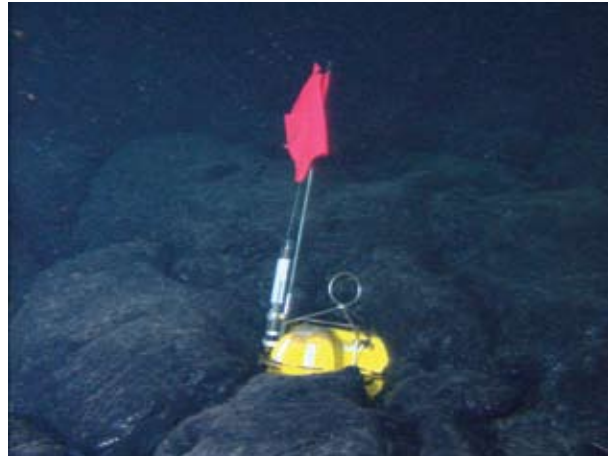
Ocean bottom seismometer partially buried in new lava flow on the East Pacific Rise approximately 600 km south of Acapulco, Mexico. The deployment was part of an experiment monitoring microearthquakes accompanying hydrothermal activity on the plate boundary and recorded increased seismicity before the eruption. (Image courtesy of T. Shank and the Advanced Imaging Lab [WHOI], copyright Woods Hole Oceanographic Institution.)

Augustine volcano in the Aleutians, March 27, 2006. Eruptions into the stratosphere from Aleutian volcanoes pose particular hazards for airplanes on flights from the United States to Japan and China. (Image courtesy of Cyrus Read, Alaska Volcano Observatory/U.S. Geological Survey.)

variations of melts inside Earth and understanding how they ascend from depth to intrude or erupt is one of the key Seismological Grand Challenges.

Seismological monitoring is one of the primary ways of forecasting or predicting eruptions. It requires long-term baseline measurements for each volcano that allows precursory behavior to be identified. An increase in microearthquake activity and harmonic tremor as moving magma changes the shape of the volcano and fractures the surrounding rock often precedes erup-tions by several days, providing some warning of the eruption. There may be changes in the depth of earth-quakes or in their mechanism. Another promising monitoring technique is 4D tomography—making repeated images of the 3D distribution of seismic velocities within the volcanic edifice and monitoring

changes in the medium's velocity with time as cracks open or fluids migrate through them. Seismo-acoustic monitoring of infrasound signals from eruptions may be able to directly detect and recognize stratospheric ash injection and other key features of eruptions at great distances, providing rapid notification to warn aircraft of hazardous conditions.

Current eruption prediction methods are primarily empirically based, because we do not have enough information for a complete understanding of the underlying physical processes. The geometry of magmatic plumbing systems of volcanoes is poorly known. To improve scientific understanding and eruption prediction capabilities, it is essential to both improve volcano instrumentation networks and to develop advanced methodologies that can better determine the physical changes that accompany eruptions, including improvements in capabilities to image the interior of volcanic systems and to quantitatively characterize magma migration and eruption processes.

In addition to the hazards posed by volcanoes, volcanic processes are of fundamental interest because they play a major role in shaping the surface of the planet. Eruptions and intrusions of magma are the primary of forming new oceanic crust. For example, two-thirds of the Earth is covered by basaltic oceanic crust averaging 7-km thick, all formed by magma rising from the mantle at mid-ocean ridge spreading centers at diverging plate boundaries during the last 180 million years.

Hot mantle rocks partially melt and generate magma as they rise toward the surface at the mid-ocean ridge because the rapid drop in pressure in the upwelling material causes the hot rocks to exceed the melting

temperature. In contrast, melt production beneath volcanic arcs, such as the "ring of fire" surrounding the Pacific, is largely created by permeating the warm mantle wedge with aqueous fluids released from subducted oceanic plates. This addition of water lowers the melting temperature of the mantle wedge, causing partial melting and magma ascent. Although magma composition, as studied by geochemists and petrologists, can reveal the approximate conditions under which melting occurred, including pressure, temperature, and water content, the depth extent of melting and the migration pathways for magma from the deep melt production zone up to the surface can only be imaged with seismology.

Beneath mid-ocean ridges, mantle flow models and low-resolution seismic tomography suggest that partial melting occurs in a zone more than 100-km across at depths as great as 100 km, yet nearly all of it emerges at a plate boundary zone that is less than 1-km wide at the surface. It is not known whether this focusing
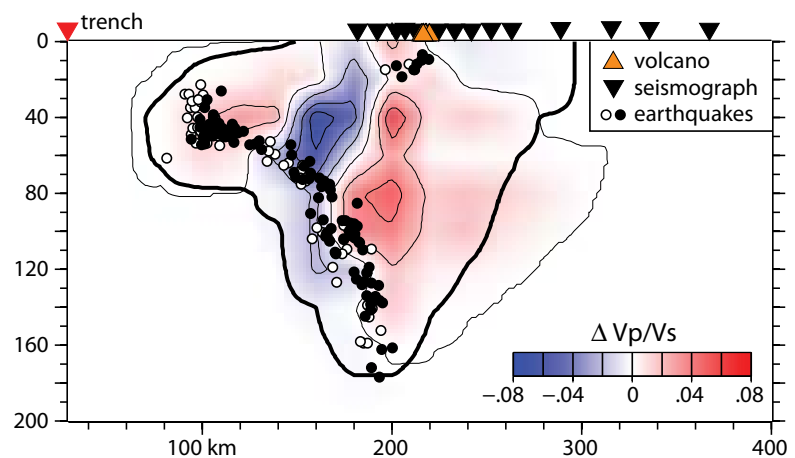
Tomographic image of the ratio between P velocity and S velocity in a subduction zone beneath Nicaragua. The highest ratio (darkest red area) indicates the presence of melts rising from near the subducted oceanic plate. The sinking plate is indicated by earthquakes extending to depths of 175 km. Fluids released from the sinking plate lower the melting temperature of material in the mantle wedge, resulting in partial melting and ascent of magmas to the volcanic arc. (Image from E.M. Syracuse, G.A. Abers, K.M. Fischer, L.G. MacKenzie, C.A. Rychert, J.M. Protti, V. Gonzalez, and W. Strauch, 2008. Seismic tomography and earthquake locations in the Nicaraguan and Costa Rican upper mantle, *Geochemistry, Geophysics, Geosystems,* 9, Q07S08, doi:10.1029/2008GC001963.)

occurs because the melt migrates horizontally through tiny cracks and pores driven by dynamic pressure gradients in the mantle, or whether it rises vertically until it reaches the overlying lithospheric plate and then flows horizontally along the sloping base of the plate back towards the ridge axis. Melt may also flow through an interconnected network of porous channels.

Volcanic eruptions also occur in intraplate settings far from plate boundaries, ranging from well-known hotspots of long-enduring volcanism such as Hawaii and Yellowstone, to tiny seamounts in unexpected places such as the outer rises seaward of subduction zones. There is much debate about the origin of the magma in these settings, and seismological imaging needs to be improved to evaluate whether thermal plumes or other structures are responsible for the volcanism.

KEY QUESTIONS AND ISSUES

- Are there upwelling plumes from deep in the mantle that undergo pressure-release melting similar to that beneath mid-ocean ridges? If so, what is the depth extent of melting?
- Is there widely distributed melt in the oceanic asthenosphere that finds its way to the surface whenever some tectonic process cracks the overlying lithospheric plate?
- What is the physical state of volcano plumbing systems and how do they change with time?

- How does melting develop above subducting slabs and by what processes and geometric pathways does it ascend?
- Does magma pond at the base of the crust and thicken the crust by under-plating? Where is melt stored within the crust before erupting?
- Why do some magmas intrude while others erupt?
- How do volcanoes and earthquakes interact?
- How do volcanoes interact with each other?

SEISMOLOGICAL APPROACHES AND NEEDS TO MAKE PROGRESS

- Densify long-term broadband seismic, geodetic, and infrasound instrumentation around active volcanic provinces on continents and islands. Imaging deep structure requires large seismic array apertures, and hence OBS deployments around islands.
- Conduct 4D active-source studies and ambient noise studies of volcanoes to quantify temporal changes in volcanic systems.
- Obtain experimental constraints on seismic velocity and attenuation properties of rocks with melts for comparison with data.

- Provide open access to data from volcano observatories, with improved data accessibility and metadata.
- Form a "learning from eruptions" program to increase public awareness of volcanic hazards.
- Increase funding to develop an external grants programs that support seismological research on volcano hazards and enhance the National Volcano Early Warning System (NVEWS).

Four-Dimensional Monitoring of Volcanoes Using Ambient Seismic Noise

Seismic noise has traditionally been viewed as a nuisance that obscures transient seismic signals, making it more difficult to detect small earthquakes or to image deep Earth structure. However, because background noise is continuously generated by physical sources, such as ocean waves interacting near the coasts, it contains seismic waves that propagate coherently across arrays of seismographs. Although ground motion complexity makes it appear random, by correlating the recordings at two stations and averaging over long time periods, a coherent signal can be extracted, yielding a seismogram equivalent to what would be produced by seismic waves propagating from one station to the other. By combining noise data from many station pairs, a 3D tomographic image of subsurface velocity structure can be constructed. If this procedure is repeated over time, a 4D representation of temporal variations in the medium can be obtained.

This method of using seismic noise provides a tremendous opportunity for monitoring of temporal changes in structure around volcanoes. Seismic noise analysis of Piton de la Fournaise volcano on Réunion Island in the Indian Ocean demonstrated that short-term (few days) changes in velocity in the volcanic edifice on the order of 0.05% could be recognized and mapped. Before each of six monitored eruptions occurring between 1999 and 2007, decreases in velocity began a few weeks before the eruption and increased in intensity up to the time of the eruption. The total velocity change was greater for the larger eruptions. The decrease in velocity was probably caused by opening of near-surface cracks in the volcanic edifice as it was inflated by increased pressure within the underlying magma chamber. Maps of the velocity changes show that different parts of the volcano were affected in the precursory activity leading up to different eruptions.
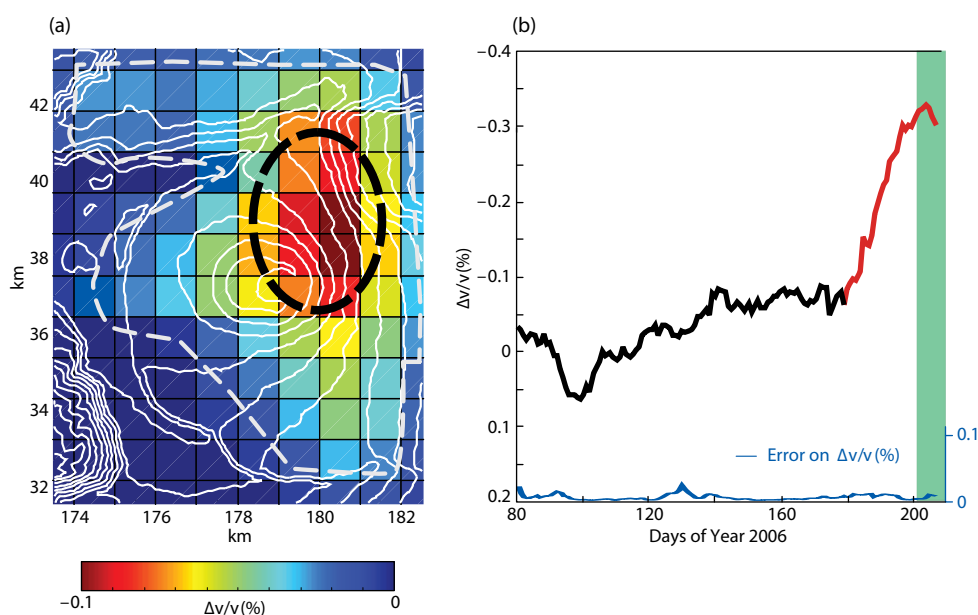
(a) Map of the cumulative changes in seismic velocity that had occurred just before the September 1999 eruption of Piton de la Fournaise volcano, Réunion. White dashed line shows the limit of coverage. Solid white lines are topographic contours. Black dashed oval is a region of normally high velocity thought to be an effect of solidified dikes associated with the zone of magma injection. For this small eruption, the high-velocity regions decreased in velocity; the maximum change was about 0.1%. (b) Velocity changes before a larger eruption in July 2006 reached about 0.3% shown by the red curve. Green shaded area indicates period of eruption. (Reprinted with permission from Macmillan Publishers Ltd.: F. Brenguier, N.M. Shapiro, M. Campillo, V. Ferrazzini, Z. Duputel, O. Coutant, and A. Nercessian, 2008. Towards forecasting volcanic eruptions using seismic noise, *Nature Geoscience*, 1:126–130, doi:10.1038/ngeo104, ©2008.)

GRAND CHALLENGE 7.
WHAT IS THE LITHOSPHERE-
ASTHENOSPHERE BOUNDARY?

Understanding the evolution and coupling of lithosphere and asthenosphere throughout Earth history is crucial to elucidating the dynamics of plate tectonics and continental evolution, and constitutes a Seismological Grand Challenge. Lithosphere, the mechanically strong outer shell of the Earth composed of crust and uppermost mantle, forms the tectonic plates. Lithosphere varies in thickness from 0 km at mid-ocean ridges to perhaps 250 km or more under cratons—the ancient and relatively stable hearts of continents. The asthenosphere is the mantle below the lithosphere, which flows and deforms to accommodate and perhaps drive plate motions. Both can

be viewed as rheological manifestations of a thermal boundary layer for the overall mantle convection system, but there is also a seismological expression of the boundary between the lithosphere and asthenosphere that is not understood, and possibly even the terminology is now outmoded.

The thermo-chemical evolution of continental lithosphere is linked to the processes by which continental crust forms. Continental crust began forming more than 3.8 Ga. By 2.7 Ga, continental cratons seem to have stabilized as regions of compositionally buoyant and stiff mantle lithosphere isolated from mantle
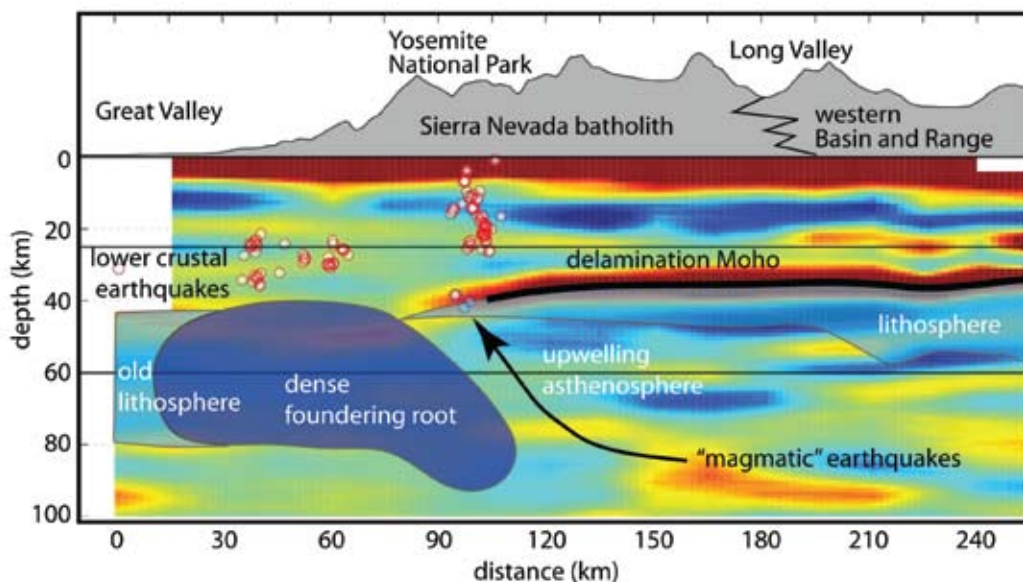
Seismic velocity discontinuities beneath the Sierra Nevada, imaged by EarthScope instruments, reveal regions of detaching lower crust beneath the mountain range, demonstrating the complexity of continental lithosphere evolution. (Image updated from original published in H. Gilbert, C. Jones, T. Owens, and G. Zandt, 2007. Imaging Sierra Nevada lithospheric sinking, *Eos Transactions, American Geophysical Union*, 88(21):225, 229.)

convection due to their relatively low temperatures, distinct composition, grain size, or other properties. Continents subsequently generally increased in size by accretion, and seismic studies of lithospheric velocity discontinuities show that these ancient accretion boundaries remain weak and continue to influence continental dynamics, magmatism, seismicity, hydrothermal, and other key processes. The deep crust and uppermost mantle also destabilize and delaminate under certain conditions, forming "drips" in which dense lithospheric roots sink into the underlying asthenosphere. Seismic imaging has recently revealed that this process occurs under the southern Sierra Nevada mountains in California and in other locales. Small-scale convective instabilities in the asthenosphere also appear to play important roles within continents, eroding geochemically distinct old mantle, and controlling melt dynamics at the lithosphere-asthenosphere boundary. Lateral movement of lithosphere is also important; stacking and thrusting of lithosphere play key roles in continental evolution and create features that persist over billions of years. Seismology is critical to investigating and understanding these structures and processes, as available surface outcrops are very limited.

Oceanic crust continually forms at mid-ocean ridges. Oceanic lithosphere thickens as it cools and moves away from the mid-ocean ridge, and from zero age to ~ 80 million years old, the thickening is as predicted by conductive cooling models; however, older oceanic lithosphere is thinner than these models predict. It is hypothesized that small-scale convection and/or reheating of the plate play major roles in this phenomenon, but the exact nature of this process is uncertain and the subject of many seismic imaging efforts. The minerals in basaltic oceanic crust and cooled upper mantle make the oceanic lithosphere denser than its continental counterpart. Because of this density difference, cold oceanic lithosphere usually subducts at convergent plate boundaries, and the age of the most ancient oceanic crust is only about 180 million years.
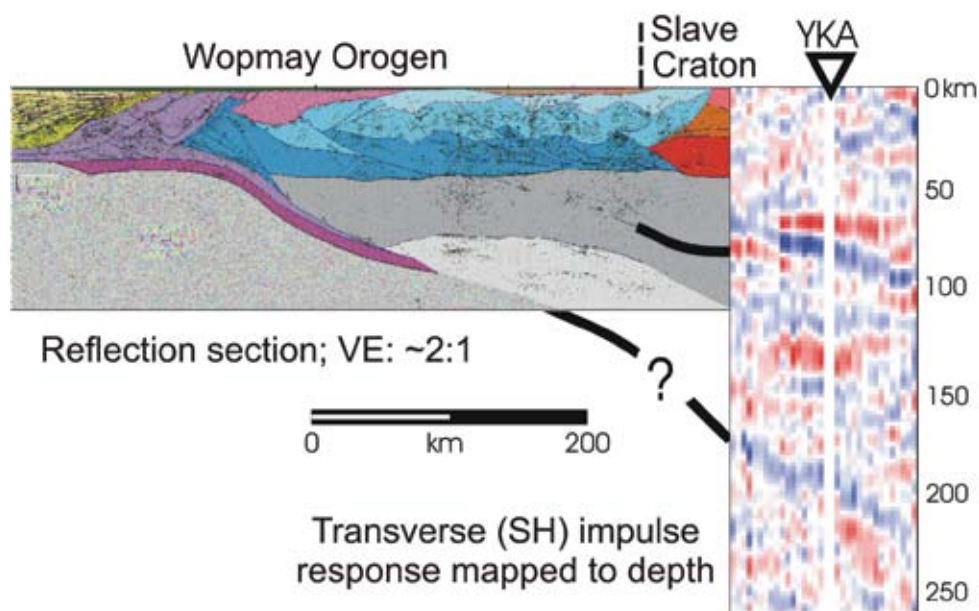
Example of seismically imaged ancient continental lithospheric sutures that have persisted into the present. The left-most portion of the figure shows lithospheric fabric from the controlled vibroseis source SNORCLE experiment. The right part of the figure, based on passive-source imaging of signals from distant earthquakes, shows these sutures extending under the ~ 2.7 Ga Slave craton in western Canada to depths exceeding 200 km. (Image courtesy of M. Bostock.)
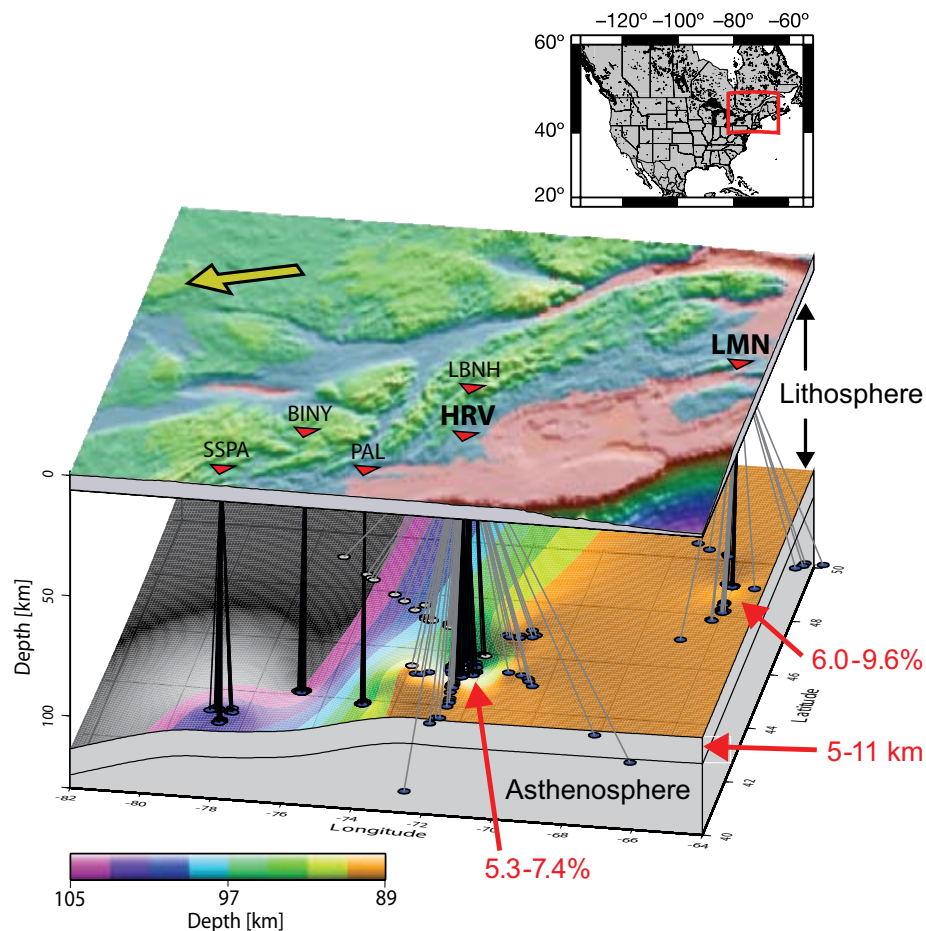
Seismic velocity contrasts possibly associated with the lithosphere-asthenosphere boundary under New England. As shown by the red text, the apparent transition from the lithosphere to the asthenosphere occurs at depths of 89–105 km and is associated with an S-wave velocity decrease of 5–10% over a depth range of 5–11 km. This velocity gradient is too sharp to be explained by a purely thermal boundary between the lithosphere and asthenosphere, and suggests that the asthenosphere is more hydrated or contains a small percent of partial melt. (Image from C.A. Rychert, S. Rondenay, and K.M. Fischer, 2007. P-to-S and S-to-P Imaging of a sharp lithosphere-asthenosphere boundary beneath eastern North America, *Journal of Geophysical Research*, 112, B08314, doi:10.1029/2006JB004619.)

A distinct zone of low seismic velocity occurs beneath oceanic lithosphere, presumably associated with the low-viscosity asthenosphere, and may extend over more than 100 km in depth. The low seismic velocities are caused by some combination of temperature, melting, hydration, and grain size. Low velocities are often also imaged beneath continental lithosphere, but the subcontinental low-velocity zone structure is more complex. In the vicinity of the asthenosphere-lithosphere transition, distinct seismic velocity changes have been detected, as well as changes in the character of anisotropy. This seismic velocity change has been used to map apparent lithospheric thickness variations, although the relationship between the seismic and mechanical features is still uncertain. It may be that the lithosphere-asthenosphere boundary is not simply a passive feature, but is influenced by small-scale mantle convection and the motion of overriding lithospheric "keels."

Lithospheric-scale seismology is being revolutionized by new data from large-scale seismometer deployments such as the USArray component of EarthScope, and by new techniques such as S-wave receiver functions and seismic noise tomography, but many challenges to understanding the evolution and structure of Earth's lithosphere and lithosphere-asthenosphere boundary remain.

KEY QUESTIONS AND ISSUES

- How did the cratonic interiors of continents form, what is their composition, why did they stabilize, and how stable are they over Earth history?
- In what ways, and by what mechanisms, do pre-existing structures such as ancient faults or sutures affect modern-day deformation, magmatism, seismicity, and other processes?
- What aspects of melting, grain-scale, and rock-scale processes cause velocity anisotropy, and how can we use knowledge of these causes to deduce the flow and strain state of the lithosphere and asthenosphere?
- What exactly is the asthenosphere? Why is it weak, and why does it have low seismic velocity and high attenuation? What controls the properties and configuration of the lithosphere-asthenosphere boundary?

- Where and when do small-scale convection and lithospheric delamination (detachment and sinking of deep crustal layers) occur?
- Where does convection occur in the ocean asthenosphere and does it relate to surface features?
- Why do intraplate earthquakes occur far from active plate boundaries?
- What is the role of melt, water, other volatiles, and composition in modulating the stability and instability of the lithosphere?
- How are continental crust and lithosphere assembled? How deep do boundaries associated with accreted terrains (chunks of crustal material added to continental margins) extend?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Enhance and continue deployment of dense portable and permanent seismic arrays on continents and on the ocean floor to provide critical observations of discontinuities, anisotropy, attenuation, and small-scale heterogeneity of the lithosphere and asthenosphere.
- Provide access to high-performance computing to enable development of new computational methods for demanding full waveform analysis and inversion.

- Acquire inexpensive, abundant seismometers for large-scale active- and passive-source deployments to image 3D lithospheric structures.
- Encourage close collaboration among geoscientists across a range of disciplines to better understand the complex roles of fluids and variable rheology, and to reveal the geologic history of the lithosphere.

Intraplate Earthquakes

The theory of plate tectonics predicts that most earthquakes result from repeated accumulation and release of strain at the contacts between differentially moving plates. However, plate tectonic motions do not readily account for earthquakes located within the interiors of oceanic and continental plates. These "intraplate" earthquakes present fundamental challenges to understanding how strain accumulates and what the associated seismic potential and hazard are for intraplate regions. For example, large areas of Australia, North America, Asia, and Europe experience intraplate earthquakes, some of which are catastrophically large. Three large earthquakes in North America occurred in 1811–1812 in the Mississippi River valley of the central United States and a large event in 1886 severely damaged Charleston, South Carolina. Some other intraplate earthquakes, such as those in Hawaii, are associated with volcanic processes. Interactions between lithospheric and asthenospheric systems may be the cause of these events, but the mechanisms are not known.

Plate interiors do not appear to experience significant strain over long periods of geological time, nor have GPS measurements detected significant strain rates in areas of past large intraplate earthquakes. However, paleoseismologists, who study historic faulting events, have found geological evidence of repeated large earthquakes over thousands of years in intraplate environments like the New Madrid seismic zone of the central United States. There are many ideas and speculations on why intraplate events occur, but no consensus has emerged on how they are generated or how they continue to occur over many earthquake cycles. Intraplate earthquakes also present significant seismic hazards, especially because they can affect densely populated regions with little preparation for seismic shaking. The existence of intraplate earthquakes remains a deep scientific mystery with strong societal implications that needs to be solved by innovative approaches.
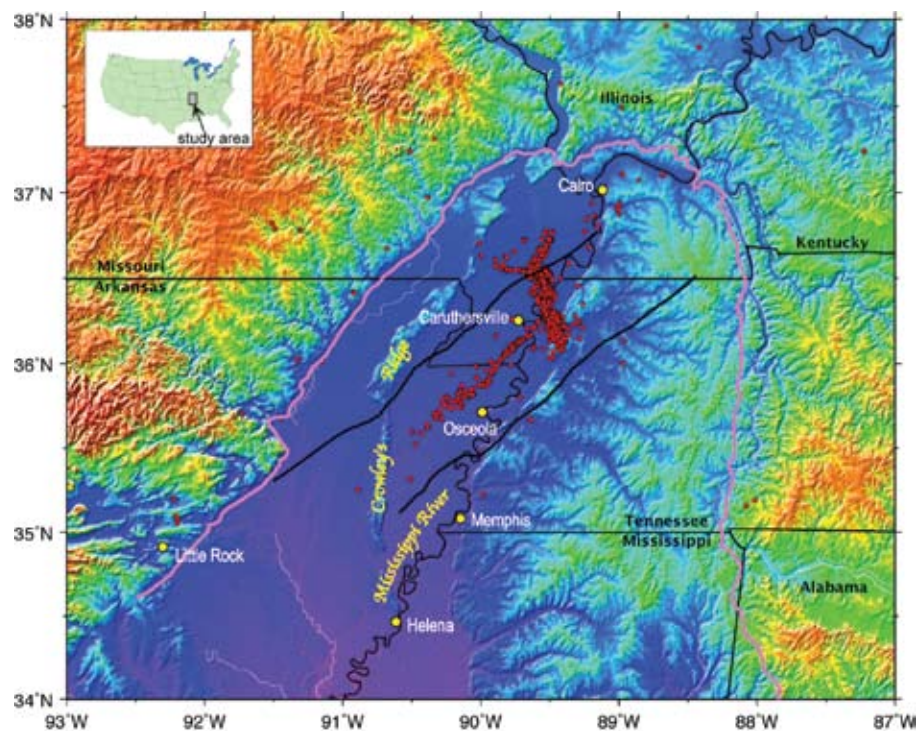
Intraplate seismicity of the New Madrid seismic zone in the central USA superimposed on a topography map with warmer colors indicating higher elevations. The red circles are earthquake locations from local seismic network analyses. The magenta line shows the boundary of the Mississippi embayment structure that, geologically, is an incursion of the Gulf of Mexico coastal plain. Thick black lines show the approximate boundary of the Reelfoot Rift zone, an ancient (approximately 500 million year old) rift that has been subsequently covered by recent Mississippi embayment sediments. Ancient faults of the Reelfoot Rift have presumably been reactivated to form the complex fault structures seen in the distribution of earthquakes. This region has experienced at least four series of large earthquakes over the past 2500 years, including three with magnitudes of 7.0, 7.2, and 7.5 in 1811–1812. (Image courtesy of M.B.Magnani.)

GRAND CHALLENGE 8.
# HOW DO PLATE BOUNDARY SYSTEMS EVOLVE?

Processes occurring at plate boundaries result in some of civilization's greatest natural hazards—great earthquakes and active volcanoes. Plate boundary processes also strongly influence Earth's surface over broad regions and drive global events such as mountain building, magmatic evolution of continental lithosphere, back-arc rifting, and crustal extrusion caused by continental collisions. A Grand Challenge in which seismology plays a major role is understanding the evolution of the multiscale processes that occur in the widespread deformed zones adjacent to plate boundaries and how they are linked to the natural hazards and geology of these regions.

Coordinated geophysical networks incorporating diverse types of sensors are required to understand the dynamics of broad plate boundary systems in both continental and oceanic regions. Seismic instrumentation provides data for determining earthquake locations and fault plane orientations, detecting low-amplitude tremors, and imaging plate structure. Geodetic instrumentation enables mapping of strain accumulation and release, at a variety of strain rates, providing records of deformation that constrain plate rheology. The rapid growth of recent seismological and geodetic observations is allowing us to identify the roles that geologic variations play in driving the development of boundary fault systems, deformation, and seismicity.

Project EarthScope is one example of a modern approach to studying plate boundary systems using integrated geophysical observations and analyses. Dense deployments of seismometers, GPS stations, and strainmeters as part of USArray and the Plate Boundary Observatory (PBO) are providing data that are transforming our understanding of the plate
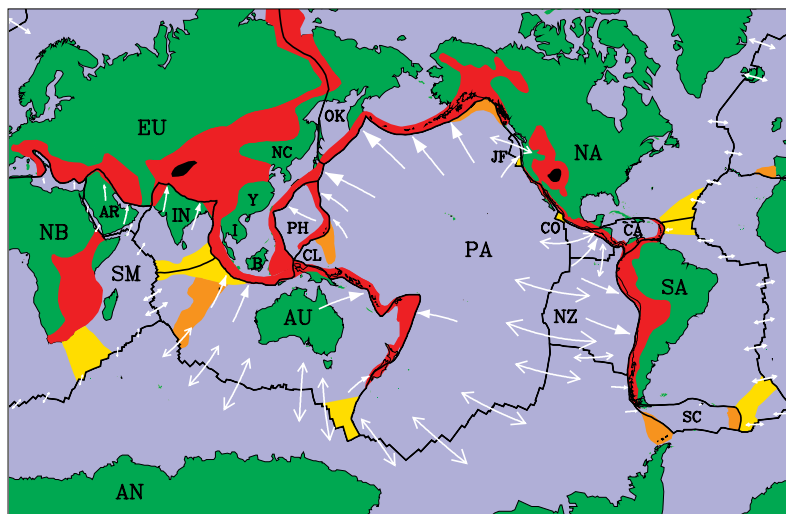
Comparison of the idealized rigid plate boundaries (thin lines) and the adjacent broad regions currently undergoing diffuse deformation (red) as indicated by seismicity, topography, and other evidence of faulting. Source: http://www.unavco.org/

Students in the SCEC undergraduate internship programs visiting SAFOD site at Parkfield during its active drilling phase in 2004. (Figure courtesy of T. Jordan.)
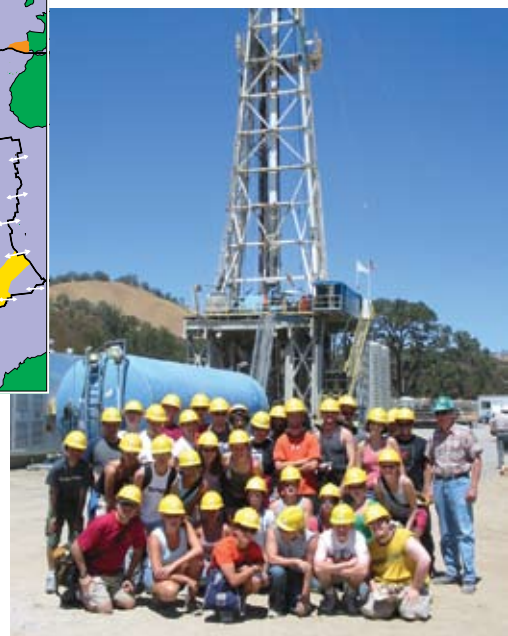
boundary. For example, focused research in the Pacific Northwest using the EarthScope observations is beginning to unveil the history of subduction of the Juan de Fuca Plate and its connection to geologically active tectonic processes throughout the western United States, including the Yellowstone hotspot, the Great Basin, and the Rio Grande Rift. The San Andreas Fault system is one of the most-studied plate boundaries on Earth, with extensive seismological, strain, drilling (e.g., SAFOD), geomorphology, and geodetic data collection efforts. Through EarthScope, seismologists are now mapping the deeper structure of the plate boundary in great detail, revealing how the pattern of crustal deformation is related to the structure, composition, and physical properties of the lithosphere and asthenosphere.

Oceanic plate boundaries are just as complex and diffuse as continental plate boundaries, but we have relatively little data at present to constrain their deep structures and processes. Melting at mid-ocean ridges is a passive process responding to distant plate forces. The newly generated crust has a uniform thickness of 7 km. Partial melting of the upwelling mantle initiates at around 100 km depth. The oceanic crustal formation process therefore cycles large volumes of the mantle through the melting zone, generating a compositional heterogeneity between the crust and underlying residual mantle that cools to become oceanic lithosphere. Melt pathways generated by this process remain enigmatic, largely due to limited data and instrumentation presently available for study of seafloor processes. Larger instrument deployments are required to better constrain and improve understanding of both the small- and large-scale structures involved in this seafloor-spreading process.

In plate boundaries regions with dense geophysical instrumentation, seismologists are now quantifying the distribution of deformation and imaging the primary structural and geologic units. By coupling the forces acting at plate boundaries with their structure and rheology, we can begin to build dynamic models of these systems to better understand fundamental processes of Earth's plate tectonic system.
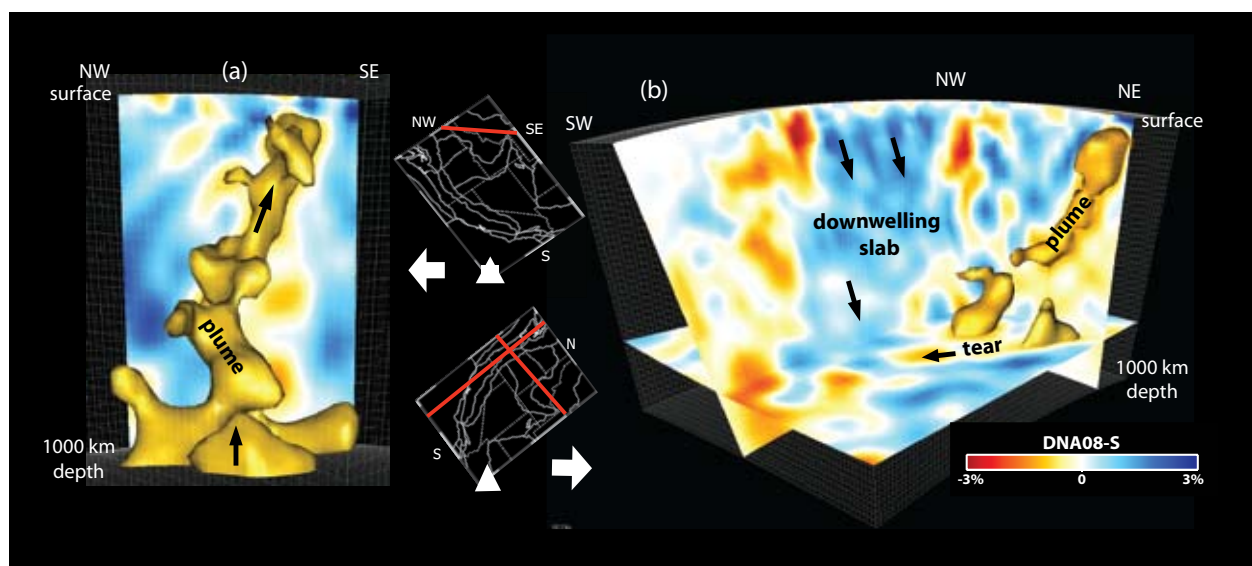
Tomographic velocity models of the upper 1000 km of the Earth beneath the western United States. Orange regions represent low seismic velocities interpreted as warm upwelling regions that may be associated with surface volcanism. Blue regions represent high seismic velocities interpreted as cool downwellings that take the form of more planar curtains sinking into the mantle. The subducting Juan de Fuca slab has been disrupted by an upwelling plume, which appears to have torn the slab from north to south. (Image courtesy of R. Allen.)
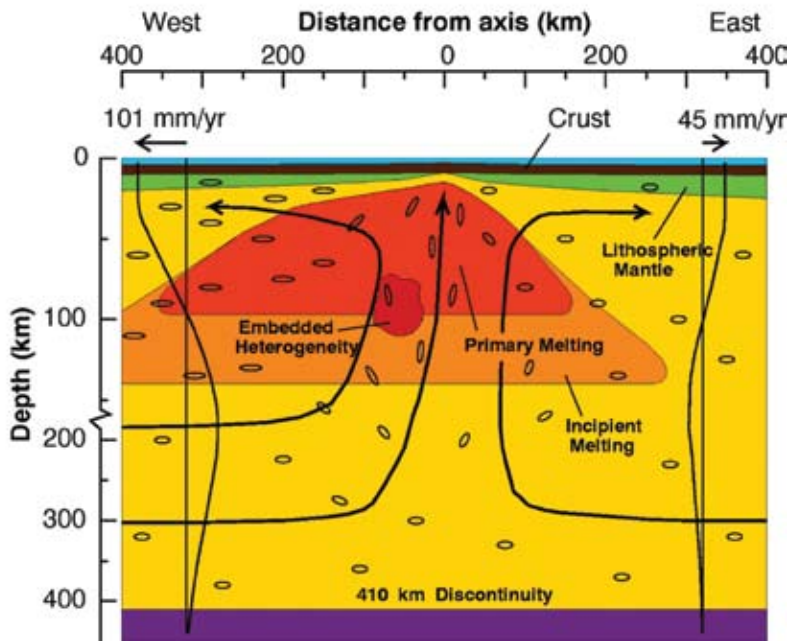
Interpreted cross section from the Mantle Electromagnetic and Tomography (MELT) experiment across the East Pacific Rise. The seismic imaging and anisotropic structure is interpreted to show an asymmetrical melting region extending to 100 km depth. Upper mantle material is being cycled through the melt zone, which is reflected in the composition of oceanic crust. (Image from MELT Seismic Team, 1998. Imaging the deep seismic structure beneath a mid-ocean ridge: The MELT Experiment, *Science*, 280(5367):1215–1218, doi:10.1126/science.280.5367.1215. Reprinted with permission from AAAS.)

KEY QUESTIONS AND ISSUES

- Is surface deformation controlled by crustal properties and stresses or by forces transmitted to the surface through the lithosphere?
- How do accretionary prisms at subduction zones evolve, what are the seismogenic hazards of splay faults that cut into the prisms, and what is their influence on trench migration?
- Are mantle wedges strongly coupled or decoupled from subducting slabs?
- How does continental lithosphere develop in back-arc basins behind subduction zones?
- How do sinking slabs interact with localized and large-scale upwellings?

- What causes deep earthquakes and what are the stress and thermal conditions in deep slabs?
- What controls the localization and segmentation of extension in rift zones and at mid-ocean ridge spreading centers?
- How and why do ocean spreading center ridge jumps occur, and what is their relation to deeper structure?
- How much lateral transport of melt is there along ridge segments and between ridges and hot spots?
- How is continental deformation in plate boundary zones accommodated at depth? What role is played by small-scale convection in driving broad deformation zones around plate boundaries?

- Deploy integrated geophysical observatories and networks with long-term operation in multiple plate boundary environments to quantify the complex systems.
- When deep drilling is performed, deploy borehole seismometers at depth, particularly in close proximity to active faults, as is the case at SAFOD.
- Deploy active- and passive-source seismic sensors in large numbers in back-arc basins, coordinated with geodetic, geologic, and geochemical investigations, to understand the creation of continental lithosphere, back-arc spreading, and trench migration.

- Deploy large numbers of OBSs in diverse mid-ocean ridge spreading environments to image the full melt-generation process that creates new oceanic plate material.
- Acquire 4D multichannel active-source seismic images with coordinated drilling at active margins.
- Conduct large-scale 3D passive imaging experiments along subduction zones.
- Encourage multidisciplinary research projects linked to hazard programs in regions of active tectonic deformation, especially in poorly understood and at-risk regions in the developing world.

Plate Boundary Field Laboratories

Dense instrumentation facilities, high-resolution 3D seismic imaging, and deep drilling into active fault zones are essential approaches to understanding complex plate boundary systems. The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) experiment is investigating the interface between the subducting Philippine Sea plate and the overriding continental plate along the Japanese margin, the site of prior magnitude 8 megathrust earthquakes. NanTroSEIZE is an international experiment; the American component is part of the MARGINS initiative and the Integrated Ocean Drilling Program (IODP). Other large-scale efforts are being pursued in different environments, linking multidisciplinary observations into large field laboratories. One of the primary goals of such field laboratory experiments is to understand

what fault properties control the transition between sections that slip aseismically and sections that slip primarily in earthquakes. Extensive subsurface mapping and monitoring using a variety of seismological and nonseismological techniques is central to these efforts. Rock samples from the drill holes can be carefully studied to understand their physical properties. Instruments can be installed downhole to study in situ rock properties and to monitor deformation and any small earthquakes that occur on or in the vicinity of the major faults. In situ measurements of thermal and hydrological properties are also part of key field laboratory efforts (Updated figure from http://publications.iodp.org/preliminary_report/314/314_f2.htm provided by H. Tobin).
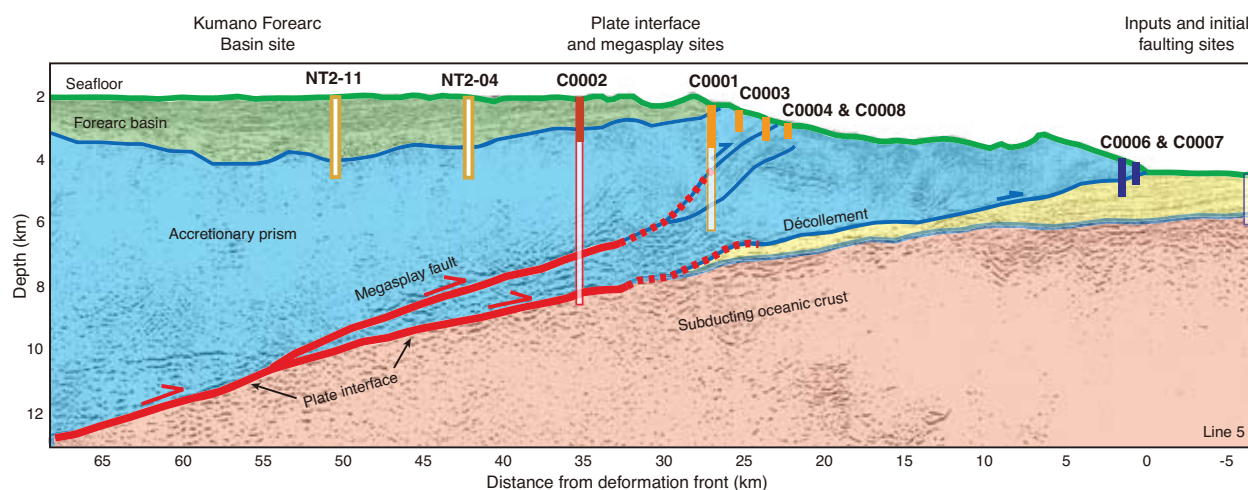
Deep Earthquakes

The mechanism responsible for generating earthquakes at great depth is still unknown. Sliding along a dry fault should be prohibited by the tremendous pressures at depths greater than 50 km, which would cause the frictional resistance to sliding to exceed the strength of rock. Yet, earthquakes are observed down to depths of 700 km within subducting slabs of cold lithospheric material. Proposed mechanisms include high pore pressures (and hence reduced normal stresses on faults) caused by water escaping from hydrous minerals (dehydration embrittlement), sudden loss of strength associated with metastable phase transitions along shear planes (transformational faulting), and runaway ductile shear instabilities, possibly including fault zone melting. These notions make predictions that can be seismologically tested. For example, seismic imaging should reveal the existence of a seismically low-velocity metastable wedge of olivine if deep earthquakes are caused by this phase transition, and there should be a lack of identically located repeating events for the mechanisms of dehydration embrittlement and metastable phase transitions. Specially designed instrument deployments are necessary for improving constraints on deep earthquake processes.
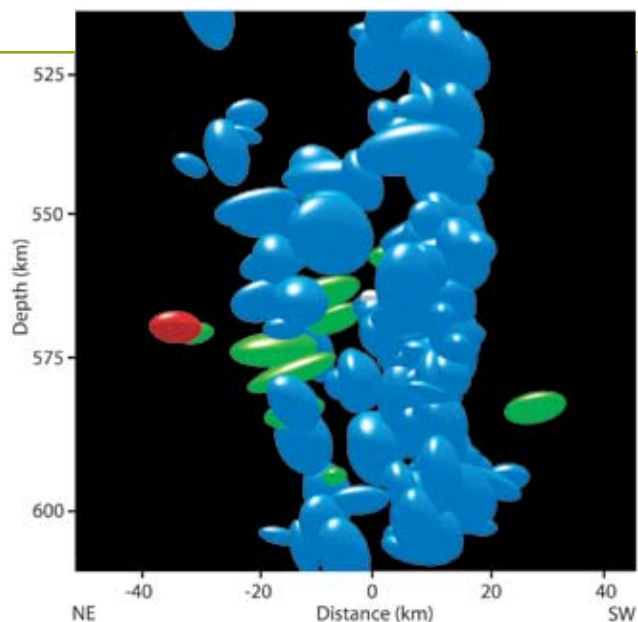
Edge-on view of deep seismicity in the Tonga subduction zone, with earthquake locations indicated by their 95% confidence ellipsoids; background seismicity is shown in blue. Most earthquakes occur within the seismically active cores of deep slabs, but aftershocks of a large 1994 earthquake (green ellipsoids) and the last subevent of the mainshock (red ellipsoid) are located outside the normal seismic zone, demonstrating that mantle material around the slab can shear during a large earthquake, likely due to transient high strain rates. (Image courtesy of D. Wiens.)

GRAND CHALLENGE 9.
HOW DO TEMPERATURE AND COMPOSITION VARIATIONS CONTROL MANTLE AND CORE CONVECTION?

Understanding the large-scale patterns of mantle and core flow both today and in Earth's past is one of the Grand Challenges confronting seismology and other Earth science disciplines. Issues ranging from the thermal history of the planet to the driving forces of present-day tectonics to how the geodynamo generates the magnetic field and why it undergoes spontaneous reversals are intimately linked to this topic. Seismology has contributed greatly over the past three decades to constraining present-day deep mantle and

core structures, and improved resolution is steadily being achieved as data accumulate and new analysis methods are developed. A profound result of recent advances is the recognition that large-scale chemical heterogeneity is present in the deep mantle and mantle convection is now being considered in the framework of thermo-chemical dynamics, as has long been the case for core convection.

The very large-scale 3D elastic wave velocity structure of the deep mantle is now fairly well known and is characterized by two massive low-velocity provinces (one under Africa and the other under the central Pacific) surrounded by faster material. The faster material appears to be geographically related to present and past subduction zones in the upper mantle, although continuity of seismically imaged fast tabular structures throughout the lower mantle is, at best, intermittent. This observation lends support to the idea of complex mass transfer between the upper and lower mantle. The large low-velocity structures are slow features for both P-waves and S-waves, but the S-wave velocity reductions are larger than would be expected if the material were just relatively warm. There are very strong lateral gradients in velocity structure at the edges of these low-velocity provinces, and analysis of normal modes indicates anomalously high-density material in these regions. These observations constitute strong evidence for distinct composition for these large masses in the deep mantle, and deep mantle convection must involve both thermal and chemical variations.
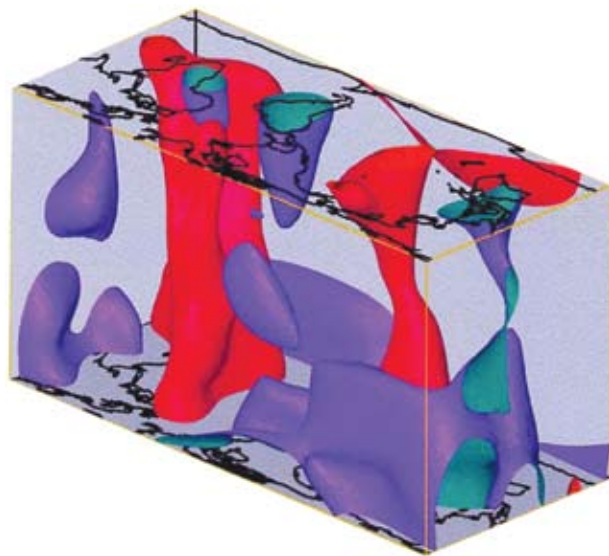
Global 3D configuration (extending from the mapped surface to the core-mantle boundary) of seismic velocity heterogeneities in the mantle as imaged by seismic tomography. Red regions have relatively low S-wave velocities, while blue regions have relatively fast S-wave velocities. The image is dominated by two enormous low-velocity regions, beneath Africa and the central Pacific plates, and by a ring of high velocities underlying subduction zones around the rim of the Pacific. (Image courtesy of A. Dziewonski).

Improving models of thermo-chemical convection requires both enhanced resolution of the structure from seismology and knowledge of the physical and chemical properties of likely constituents of the mantle. Mineral physics experiments and theory have quantified many properties of the primary minerals in the upper and lower mantle and have characterized the nature of phase transformations expected as pressure and temperature increase. Comparisons of those data with seismic observations place bounds on viable chemical and thermal variations in Earth's interior and their associated density heterogeneities. This information then informs geodynamical simulations that seek to reconcile mantle flow models with seismic observations. There remain minerals physics arguments for some level of chemical stratification between the upper and lower mantle in order to match observed seismic measurements, but new discoveries such as the probable occurrence of high-spin to low-spin transitions in iron with depth have added new degrees of freedom to the problem. Iron enrichment

of lower mantle minerals would likely increase their density and thus lower shear velocity. This scenario is a possible contender for explaining some of the properties of the large low-velocity regions in the mantle, which might be chemically distinct, dense piles of material embedded in a large-scale circulation. These piles may possibly serve as the reservoirs for geochemical tracers that are depleted in near-surface samples. In particular, radioactive elements may be preferentially enriched so that the piles could be sources of heat to drive convection in the overlying mantle.

Although the seismic velocity signature of the low-velocity provinces is clearly present high above the core-mantle boundary, seismic tomography cannot yet determine whether the low-velocity provinces are uniform structures or are made up of groups of finer structures, or whether the wide piles have a roof at some height above the core-mantle boundary in which are rooted narrow thermal plumes that rise to produce surface hotspot volcanism. This lack of resolution results
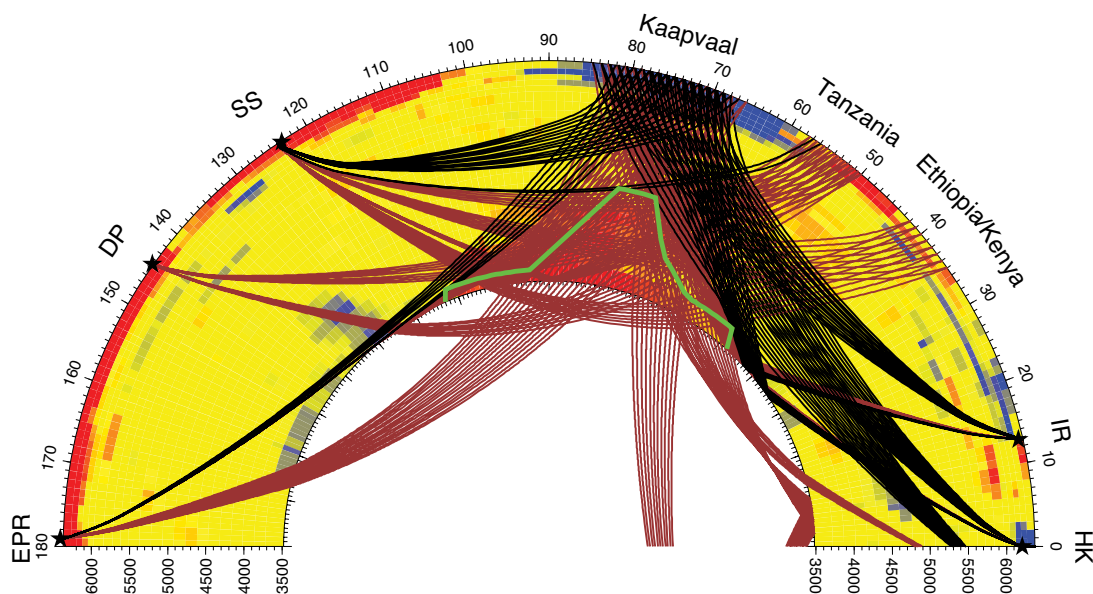
Cross section through the mantle showing how ray paths for diverse seismic phases from various source regions constrain the extent of the large, low-shear velocity province beneath Africa, which is bounded by the green outline. S-wave velocities within the province are about 3% lower than in the surrounding lower mantle. The structure extends upward more than 1000 km above the core-mantle boundary. (Image from Y. Wang and L. Wen, 2007. Geometry and P and S velocity structure of the "African Anomaly," *Journal of Geophysical Research*, 112, B05313, doi:10.1029/2006JB004483.)

from a combination of limitations in global sampling by seismic waves due to lack of seismic stations in the ocean and in the southern hemisphere, and of limitations of seismic imaging theory and applications that are currently being used. Enhanced data collection and imaging of velocity structure at every scale is essential, but there is also the need to improve global anisotropy and attenuation models, which enhance our ability to connect seismological observations to mineral physics and geodynamics.

Seismology constrains the average structure of the metallic fluid outer core and solid inner core to high precision, but it cannot resolve the convective flow field in the outer core—geomagnetic studies are the only current approach to doing so. To first order, there does not appear to be detectable seismic velocity heterogeneity in the outer core, consistent with it being a very low-viscosity fluid, but there are indications of inhomogeneous in structure in both the uppermost and

The Mysterious Inner Core

Seismology reveals that Earth's inner core is surprisingly complex. Although small (about the size of Earth's moon), the inner core plays an important role: its progressive freezing generates compositional buoyancy by expulsion of light alloy components into the liquid outer core, which serves as an energy source for the outer core convection that maintains Earth's magnetic field. In the past two decades, seismic analyses have revealed variations in elastic properties of the inner core both radially and laterally, including multiscale variations in attenuation and anisotropy. To first order, the inner core has an overall anisotropic structure, such that waves travel faster and are more attenuated from pole to pole when paralleling the equatorial plane. But, the central region of the inner core has a distinct orientation of anisotropy, and the outermost region is almost isotropic. Large-scale lateral heterogeneities occur both in latitude and longitude in the outer portions of the inner core; seismic velocities are higher, and seismic waves exhibit more attenuation in the eastern hemisphere than in the western hemisphere. There is also fine-scale (few kilometer) heterogeneity within the inner core. All of this complexity is unexpected, and has prompted mineral physics and geodynamic modeling of high-pressure iron phases and crystallization mechanisms.

Inner core heterogeneity has been exploited to detect small differences in rotation of the inner core relative to the mantle. The differential rotation was detected by observations of systematic changes in the travel time of P-waves transmitted through the inner core over several decades (a strong argument for long-term operation of high-quality seismic observatories). The travel time changes are very small, involving tenths of a second difference on the same path traversed decades apart. Travel time changes have also been observed for reflections off the inner core surface, indicating temporal changes of the near surface. The source of the torques driving either a differential rotation or wobble of the solid inner core may be electromagnetic in origin
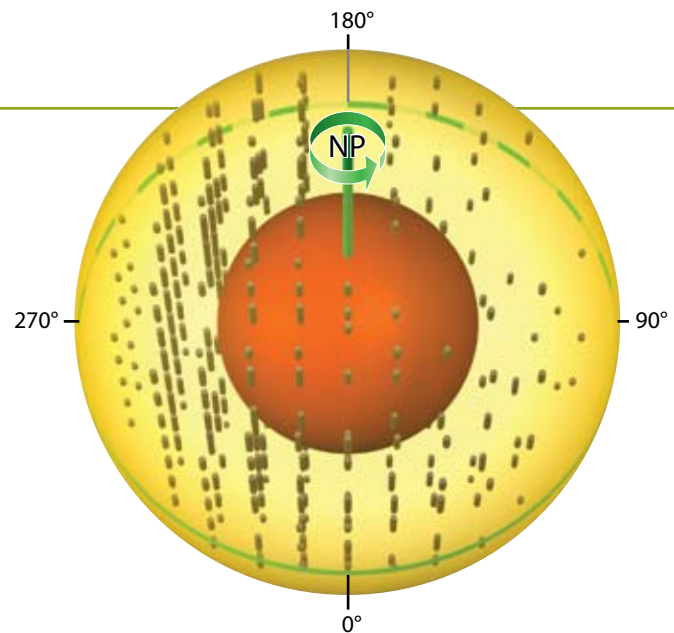
Three-dimensional distribution of anisotropic fabric within the outer part of the inner core. The rods indicate the directions along which P-waves travel fastest, with the length of the rod indicating the contrast between fast and slow velocities at each point. The outermost inner core has weak anisotropy. There is a puzzling difference between eastern and western hemispheres of the inner core. The central region of the inner core (orange ball) has a distinct anisotropic fabric that is not illustrated. (Image courtesy of X. Song.)

and related to time variations in fluid flow or gravitational in origin and related to heterogeneities at the base of the mantle. Changes in local inner core surface conditions could arise due to lateral variations in outer core convection or inner core growth rates. Combined seismological, petrological, and geomagnetic studies are needed to shed light on the mechanism of growth of the inner core, which adds centimeters per century to its radius. This process of growth is critical to the thermal evolution of the core, the cooling history of the planet, and the geodynamo.

the lowermost 100 km of the outer core. These regions plausibly have distinct chemistry associated with thermo-chemical dynamics of the core that drives the core flow regime and thereby generates the magnetic field by geodynamo action. Resolving the structure of these domains is a high priority for understanding the deep interior. The inner core is solid, but has been recently found to be surprisingly heterogeneous on many scales. It exhibits radially varying anisotropic structure, hemispherical heterogeneity, and heterogeneous attenuation properties. Seismic evidence indicates that the inner core is currently rotating slightly faster than the mantle. Close interaction among seismologists, mineral physicists, and geodynamicists is essential for evaluating the nature and consequences of these complexities.

KEY QUESTIONS AND ISSUES

- What are the scales of heterogeneity in the global mantle convection system, and what are the chemical, thermal, and mineralogical causes of the multiscale heterogeneity?
- What is the flux of material between the upper and lower mantle, and on what time scales does it occur?
- What are the relative contributions of thermal, chemical, and mineralogical variations to seismically detected heterogeneity?
- Are there large thermal plumes in the mantle, and are they related to surface hotspots?

- What is the longevity of chemical heterogeneities in the deep mantle and what is their effect on the overall convection pattern?
- What are the nature and cause of deep mantle anisotropy?
- When did the inner core form and what are its influences on the geodynamo and Earth's magnetic field?
- How is heterogeneity of the inner core related to its growth processes over Earth's history and what are the geodynamic and geomagnetic consequences of this heterogeneity?
- How do the interiors of other rocky bodies in the solar system differ from that of the Earth?

SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Expand global coverage with permanent broadband seismic stations, including the ocean basins, to improve resolution of global structure and sustain long deployments to capture time-varying processes.
- Deploy large portable arrays of three-component broadband sensors in various tectonic environments to resolve deep anisotropy and assess the fine-scale components of heterogeneity in the deep mantle and core.

- Develop and distribute large data sets to be applied in imaging methods that use finite-frequency theory and wavefield backprojection to improve resolution of deep structure.
- Encourage enhanced interdisciplinary communication among seismologists, mineral physicists, and geodynamicists through workshops, programs, and community organizations.
- Include seismic data acquisition capabilities in planetary exploration efforts.

Planetary Seismology

Buzz Aldrin deploying a seismometer on the Moon during the Apollo 11 mission. (Image courtesy of NASA.)

Seismology can potentially reveal internal structure and dynamic processes of other rocky bodies—planets, moons, and asteroids—in the solar system, if seismic sensors can be deployed and data retrieved. A very limited amount of seismic data obtained from the Moon during the Apollo program revealed unique and fundamental information about the Moon's internal structure, including thickness of the surface regolith layer, presence of a low-velocity zone near a depth of 400 km, very low seismic attenuation indicative of very small quantities of fluids in the crust, and the possible existence of a partially molten silicate core. Deployments of seismometers on other planetary bodies can potentially address many significant scientific questions, such as the existence and radius of planetary liquid cores, the extent of water and temperatures within the crust and mantle of Mars, the dimensions of the salt-water ocean on Europa, and the reason for the lack of a magnetic field on Venus. Although every planet presents formidable challenges to seismological approaches, the long reach of seismological methods can provide a bountiful return of important information that cannot be obtained by any other method.

A return of seismometers to the Moon would provide opportunities to explore outstanding basic questions, including: Does the Moon's internal structure support the model of lunar formation from ejecta of a large impact on Earth? What is the nature of the mantle-core boundary within the Moon, and what is its connection with deep moonquakes? What is the physical mechanism that controls the correlation between moonquakes and tidal stresses excited by Earth's gravitational field? Are the mechanisms of failure for deep lunar quakes similar to the mechanisms responsible for deep earthquakes on Earth? Are these events related to solid phase changes in silicate minerals? How large are lateral heterogeneities in composition and structure, as determined using 3D tomography?

A similar broad range of topics can be addressed by deploying seismometers on Mars, if engineering challenges of designing, building, and deploying rugged seismometers protected from extreme temperatures, winds, and cosmic radiation, can be overcome. Mars is likely to be relatively lacking in tectonic faulting processes, but mapping the crust and lithosphere will be feasible using artificial sources and the new seismic technique of analyzing correlated noise excited by the strong atmospheric winds. Key topics that could be addressed include the radial layering of the crust mantle and core of the planet, the distribution of groundwater/ice in the near surface, and the internal structural variations associated with the presently enigmatic bimodal surface morphology of the planet. Determining the frequency of impacts and how strongly they vibrate the surface is also of interest.
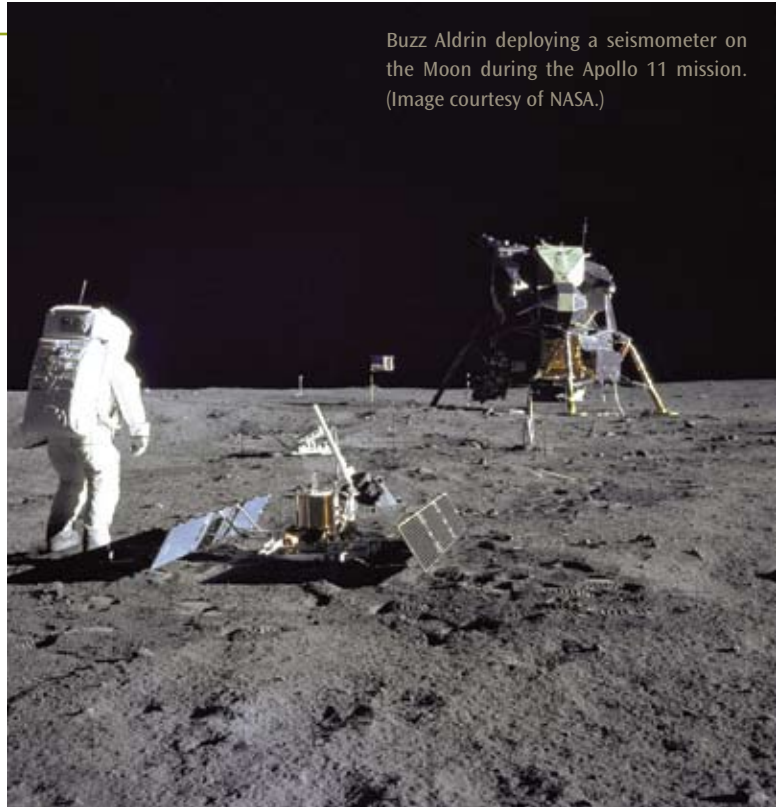
Venus and Mercury present formidable environmental challenges, but seismological technologies that can overcome them may be within reach. Smaller planetary bodies like Europa, Ganymede, and Enceladus are good targets for using seismological methods to determine the presence and extent of internal fluids. Asteroids have highly uncertain material properties, and design of seismological probes of their interiors can complement other approaches such as ground-penetrating radar. Given the great payoff from even limited seismic recordings, every mission to a solid body in the solar system should include consideration of the potential for seismological instrumentation and data collection.
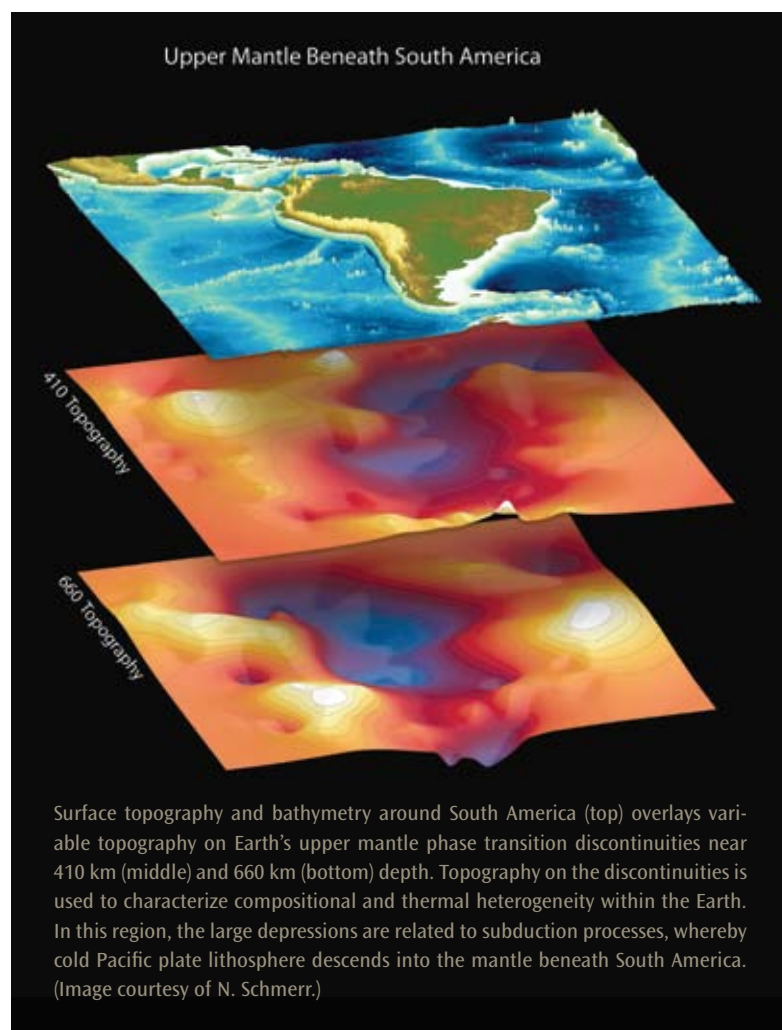
GRAND CHALLENGE 10.
HOW ARE EARTH'S INTERNAL BOUNDARIES AFFECTED BY DYNAMICS?

Internal boundaries in the Earth are associated with the primary compositional layering that resulted from chemical differentiation of the planet (the crust, mantle, and core) and with mineralogical phase changes controlled by pressure and temperature variations (the transition zone and deep mantle velocity discontinuities and the inner core boundary). These variations can produce significant accompanying changes in composition and rheology. These boundaries can thus exert a strong influence on mantle and core convection, particularly if they serve as thermal boundary layers, and their seismically determined properties can constrain internal composition and temperature when calibrations from mineral physics are available. Seismology can characterize the depth (pressure) and elasticity contrasts across internal boundaries with high precision. The frontier of research now lies in mapping the 3D topography and sharpness of Earth's internal boundaries, which are key to quantifying their mineralogical and compositional nature. The seismological methods that are needed involve waveform modeling and wavefield migrations, complementing travel-time tomography, which is better for resolving volumetric heterogeneities. Detailed imaging and interpretation of the thermal, compositional, and dynamical processes near Earth's internal boundaries are the principal components of one of the Grand Challenges for Seismology.

Radial models of the mantle include globally extensive seismic velocity jumps near depths of 410, 520, and 660 km, which are generally attributed to phase

Surface topography and bathymetry around South America (top) overlays variable topography on Earth's upper mantle phase transition discontinuities near 410 km (middle) and 660 km (bottom) depth. Topography on the discontinuities is used to characterize compositional and thermal heterogeneity within the Earth. In this region, the large depressions are related to subduction processes, whereby cold Pacific plate lithosphere descends into the mantle beneath South America. (Image courtesy of N. Schmerr.)

changes in major upper mantle minerals such as olivine. Laboratory and theoretical calibration of the pressure-temperature-composition behavior of mantle minerals allow seismic observations to be interpreted in terms of absolute temperatures and compositional models. This allows high-resolution imaging of lateral variations in depth of the discontinuities to provide direct constraints on flow across the phase transition boundaries. Tomographic images of subducting oceanic lithosphere have established that slabs either deflect and accumulate in the transition zone or penetrate directly into the lower mantle, so it is clear that transition zone boundaries can profoundly affect mantle convection. Many other upper mantle seismic reflectors have been detected over localized regions, notably under cratons and beneath back-arc basins. Understanding the cause of this seismic velocity reflectivity and how it is affected by dynamics of the

mantle wedge may fundamentally change our notions of the creation and stabilization of continental lithosphere and how it has changed through time.

Seismic reflectors in the deep mantle have also been detected, both in 3D scattering images of near-vertical mid-mantle heterogeneities that are plausibly features produced by ancient subducted slabs, and in reflections from the sharp edges of the large low-velocity provinces under the Pacific and Africa. There is also a globally intermittent reflector of seismic waves found 200–300 km above the core-mantle boundary. This boundary is now widely attributed to the recently discovered mineralogical phase transition from the most abundant mineral in the lower mantle (magnesium-silicate perovskite) to a high-pressure (post-perovskite) polymorph. Seismic waves also reveal the presence of an extensive, but intermittent,

Cross sections in a 3D seismic migration image of S-wave reflectivity in the mantle wedge adjacent to the subducting Tonga slab. Quasi-horizontal structures exist throughout the wedge that are not readily accounted for by standard upper mantle petrological models. (Image courtesy of Y. Zheng.)
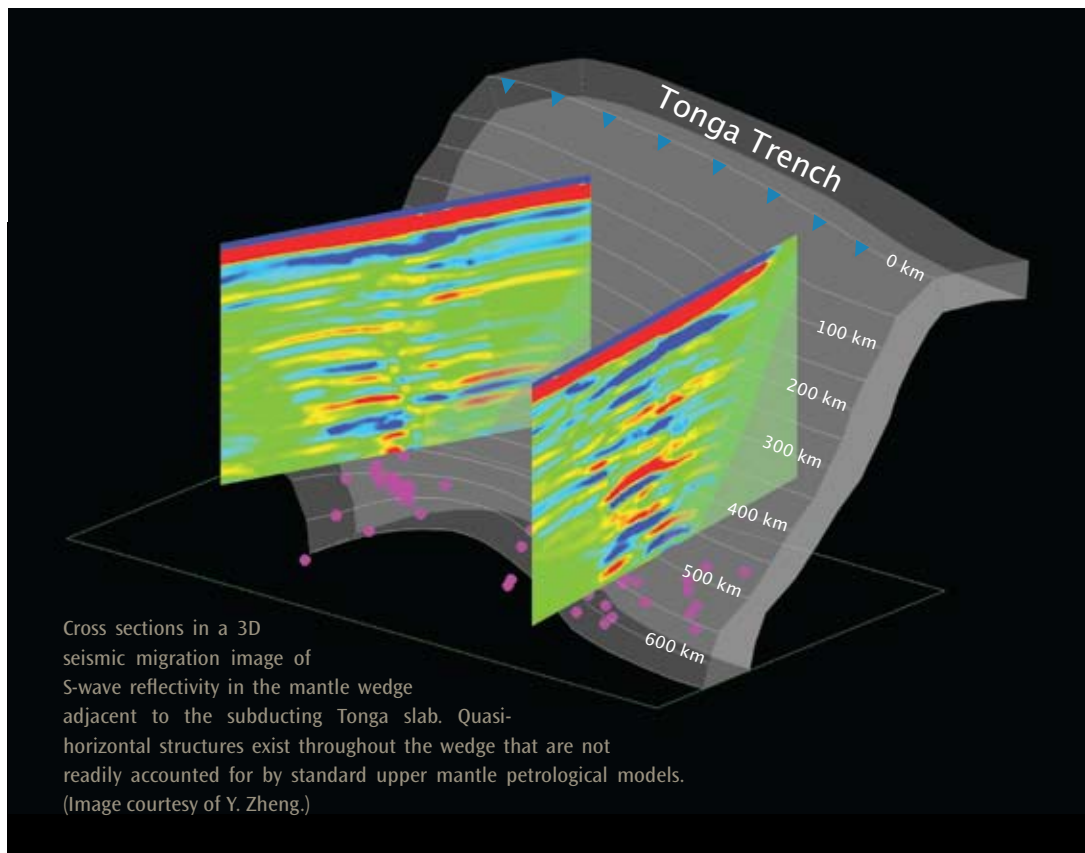
very thin (< 30 km) ultra-low velocity zone located just above the core-mantle boundary. This low-velocity zone is commonly attributed to partial melt being present in the hottest part of the thermal boundary layer, although strong chemical contrasts may also be involved. All of these seismological structures have implications for deep mantle dynamics.

Analysis of boundary layer processes provides internal temperature probes along with constraints on rheology and composition. Improved seismological constraints play a unique role in discovering and understanding these boundaries.

phase transition height above CMB [21]

0   km   310
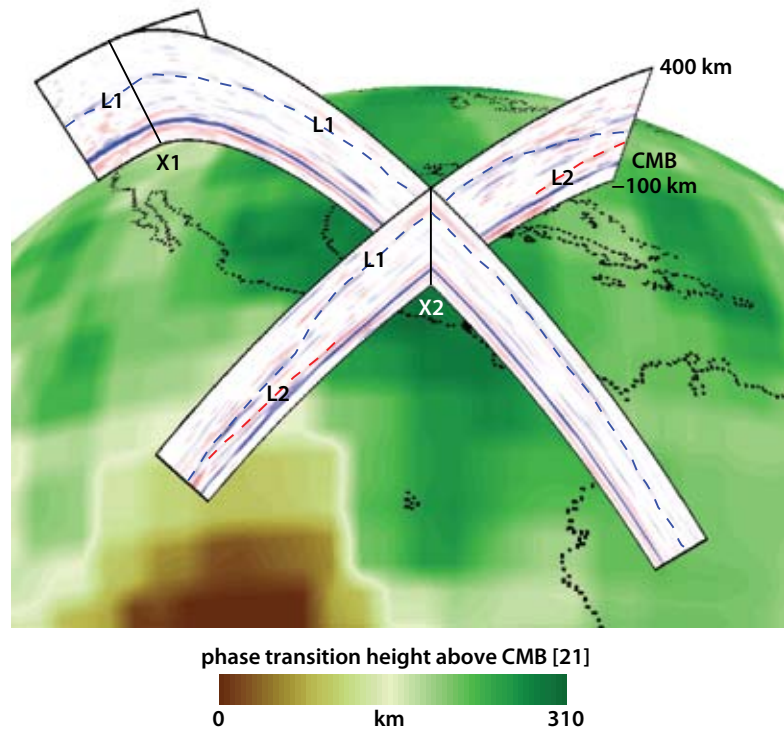
Migrated S-wave reflector images of the core-mantle boundary (2) and a deep mantle reflector about 250 km above the core-mantle boundary (1). (Image from R.D. van der Hilst, M.V. de Hoop, P. Wang, S.-H. Shim, P. Ma, and L. Tenorio, 2007. Seismostratigraphy and thermal structure of Earth's core-mantle boundary region, *Science*, 315:1813–1817, doi:10.1126/science.1137867. Reprinted with permission from AAAS.)

KEY QUESTIONS AND ISSUES

- How sharp are internal mantle and core boundaries?
- What is the multiscale topographic structure and lateral extent of mantle boundaries, including the core-mantle boundary?
- What are the effects of the transition zone boundaries on mass flux between the upper and lower mantle?
- Are there thermal boundary layers that serve as sources of mantle plumes at any of the internal boundaries?
- Is post-perovskite present in the mantle and does it exist in lenses or as a layer?
- What is the cause of the ultra-low velocity zone at the base of the mantle, and how has it evolved?

- How can seismological observations constrain heat flux across the boundaries?
- To what degree are variations in water content and chemical heterogeneity responsible for topography on mantle discontinuities?
- Can we detect time-dependent changes in boundary properties?
- Are there stable thermo-chemical boundary layers in the outermost outer and lowermost outer core?
- What causes hemispherical variations just below the inner core boundary and what is the source of deeper anisotropy?

# SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS

- Establish dense seismic arrays in key locations suitable for resolving fine-scale structure of boundaries in the upper and lower mantle and core.
- Develop enhanced seismic wave propagation methods for handling irregular boundaries and for imaging their 3D configurations as well as velocity fluctuations in the adjacent media.

- Expand global coverage of boundary structures with new sites in the ocean and at high latitudes to better constrain the structure of Earth's mantle and core.
- Foster communications with mineral physicists and geodynamicists to formulate testable hypotheses that seismology can pursue.

Core-Mantle Boundary Heat Flow

About 25 years ago, seismologists discovered a seismic velocity discontinuity several hundred kilometers above the core-mantle boundary. This boundary remained enigmatic until 2004, when mineral physicists discovered that the dominant lower mantle mineral, silicate perovskite, transforms at corresponding pressures and temperatures to a new phase called post-perovskite. This discovery has stimulated great activity in seismology, mineral physics, and geodynamics. A calibrated phase change enables bounds to be placed on the absolute temperature at great depth in the Earth, with ~ 2500°C being estimated for the seismic discontinuity. Experiments and theory predict a steep positive pressure-temperature gradient at the perovskite-post-perovskite transition, but it is possible that an even steeper thermal gradient in the hot thermal boundary layer above the core can intersect the transition twice, producing a lens of post-perovskite sandwiched between perovskite. Seismic observations support this model, with paired velocity increases and decreases observed at different depths. These velocity changes provide two estimates of temperature at closely spaced depths, enabling an estimate of the temperature gradient if a steady-state conductive boundary layer is assumed. Assuming a value of thermal conductivity then yields a direct estimate of the local heat flux from the core to the mantle. Several such estimates have now been published, finding values close to the average heat flux at the surface. Extrapolated globally, these studies imply that as much as a quarter of the surface heat flow comes from the core, though the uncertainties are large—particularly in the estimation of the thermal conductivity. These seismically derived constraints on heat flow have broad implications for mantle convection, core cooling, inner core growth, and other fundamental Earth processes driven by the global heat flux.
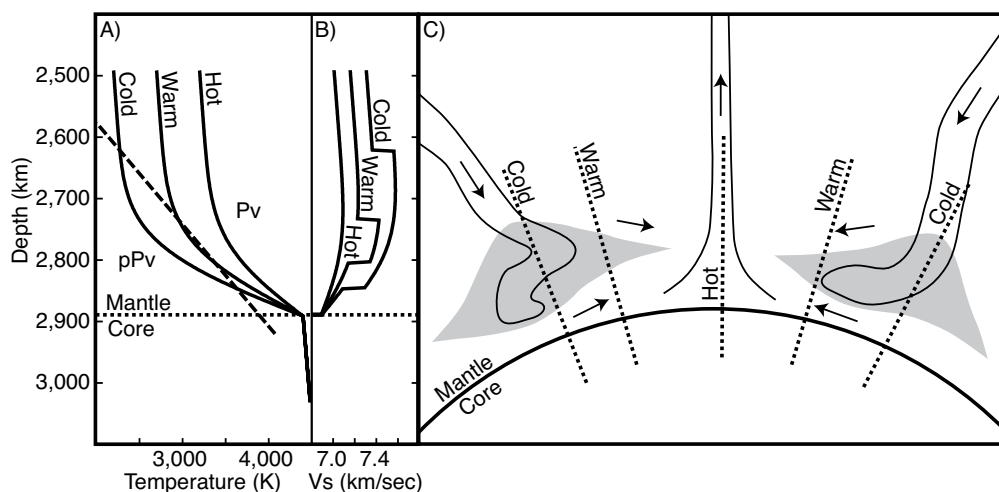
The transition from perovskite (Pv) to post-perovskite (pPv) varies with temperature and depth (pressure) as indicated by the dashed line on the left. If the temperature at the core-mantle boundary exceeds the temperature for post-perovskite stability, the steep increase in temperature with depth in the lower mantle thermal boundary layer will result in two intersections with the phase boundary. These intersections would be manifested in paired velocity increases and decreases as shown, and laterally varying "lenses" of post-perovskite as depicted on the right. Such paired discontinuities have been observed and used to estimate thermal gradients and heat flow based on the temperature calibration from mineral physics. (Reprinted by permission from Macmillan Publishers Ltd.: J.W. Hernlund, C. Thomas, and P.J. Tackley, 2005. A doubling of the post-perovskite phase boundary and structure of the Earth's lowermost mantle, *Nature*, 434:882–886, doi:10.1038/nature03472, ©2005.)

SUSTAINING A HEALTHY FUTURE FOR SEISMOLOGY

T he remarkable panoply of seismological research topics and societal applications reviewed here is the direct result of extensive investment by a number of federal agencies, industry, and universities. Sustaining the upward trajectory of seismology's diverse contributions to science and society requires continued strategic investment in future human and technical resources. Discussion of the disciplinary needs and recommendations for the future are summarized here.

BUILDING AND SUSTAINING THE PROFESSIONAL PIPELINE

Key to all undertakings in seismology is maintaining and supporting a steady pipeline of talented people with solid quantitative skills into university programs that provide undergraduate and graduate training in fundamentals and applications of seismological theory and prepare new seismologists for tomorrow's challenges. Retention of this talent and expertise in industry, national laboratory, academic, regulatory, state, and federal agency careers requires continued collaboration among academia, funding agencies, and employers to establish sustained supporting structures. The seismology workforce demands of industry are not presently being fully met and new and stronger partnerships between relevant industries (e.g., energy, insurance, engineering) and academic programs should be developed to attract undergraduates and graduate students to the discipline.

Attracting top students to this exciting and important discipline requires improved outreach that highlights its many societal contributions and exciting research frontiers. Broadly based efforts to enhance public awareness of the importance of the discipline, as conducted by Education and Outreach (E&O) efforts of IRIS, SCEC, and EarthScope as well as many university programs, are highly beneficial long-term investments that play a critical role in showcasing the importance of seismology and its numerous contributions to society.

RECOMMENDATIONS

- Further engage seismology community organizations with industry to increase awareness of opportunities in seismology among undergraduates and high school students.
- Expand E&O efforts of these organizations to promulgate public awareness of the discipline and its societal contributions, and support undergraduate and graduate training materials and enhanced educational opportunities.

ENHANCING ACCESS TO HIGH-PERFORMANCE COMPUTING CAPABILITIES

Increasingly massive seismic data sets, very large inversions for 3D and 4D multiscale models of Earth's interior, and robust forward calculations of broadband seismic ground motions for realistic, nonlinear effects of earthquake and explosion sources as well as 3D structure present enormous computational challenges that exceed the capabilities of the most advanced computers presently available. Advancing seismology research at universities and elsewhere will rely on access to resources ranging from moderate-size, in-house computer workstations and clusters to large-scale computational capabilities, such as those at national laboratories in tandem with integrated cyberinfrastructure networks such as TeraGrid. Access to high-performance computing, coupled with further improvements in the standardization and dissemination of advanced seismic software (such as is currently being pursued by the NSF Computational Infrastructure for Geodynamics [CIG] initiative), is essential to advancing the discipline, both in facilitating new methodological breakthroughs and in providing access to state-of-the-art capabilities to more institutions.

RECOMMENDATIONS

- Make available to the broad research community carefully vetted seismological software and processing tools, along with integrative data products. There is also a special need in developing coun-

tries with significant earthquake hazards to provide simple, standardized and open software tools for processing and analysis of seismic network data.
- Ensure data storage and online open access to all seismic data sets in perpetuity.

- Establish readily accessible pathways to facilitate the use of massive computer resources through academic, industry, federal (e.g., national laboratory) and other collaborations.
- Sustain instrumentation programs that provide intermediate-size university computer capabilities involving workstations and clusters.

SUSTAINING GLOBAL OBSERVATORIES

The open availability of high-quality, widely distributed recordings of ground motion lies at the heart of all seismological research and monitoring activities. Strong commitments are therefore needed to sustain continuous, long-term observations at global observatories maintained by the FDSN, the IRIS/USGS GSN, and the CTBTO IMS, as well as completion of the Advanced National Seismic System (ANSS) within the United States. Furthermore, data and co-sited instrumentation partnerships should be enhanced with DOE, DoD (e.g., AFTAC National Data Center), Nuclear Regulatory Commission, state, university, and other partners, whenever there is mutual benefit. Sustained maintenance and operation of high-quality standardized global stations is essential for national security, global monitoring of the environment, earthquake and tsunami hazard warning and response activities, and investigations of the Seismological Grand Challenges elucidated in this report. As instrumental bandwidths broaden, networks expand, and new types of observations become available in all disciplines, we need to look toward a more holistic view of monitoring that includes not just signals from traditional seismometers and accelerometers, but also complementary signals traditionally monitored and analyzed by geodesists, space scientists, meteorologists, oceanographers, glaciologists, hydrologists, and environmental scientists.

RECOMMENDATIONS
- Advance coordination with other environmental monitoring facilities and communities to establish multidisciplinary monitoring stations at global seismographic facilities, as well as to augment global seismic instrumentation.
- Share the sustained support of IRIS/USGS GSN long-term operations and equipment upgrades among all federal agencies that rely upon global seismic data as part of their operations.
- Coordinate between the academic community and international sponsors of hazard assessment and mitigation, especially in poorly studied regions in developing nations to create multi-use programs for monitoring, research, training, and capacity-building.
- Set the completion of the ANSS by the USGS as a high priority.
- Continue support for the operations of the ISC, which assembles and reprocesses catalogs from many international networks to the benefit all users of seismological bulletins.
- Deploy global ocean bottom borehole installations, guided by the International Ocean Network (ION) plans for establishing uniform global coverage of the Earth.

ADVANCING PORTABLE INSTRUMENTATION

Large pools of portable instruments are essential for seismological investigations of continental and oceanic environments at higher resolution than that afforded by the current global network of permanent stations. These resources also allow for flexibility in studying targeted regions of special interest and activity (e.g., active volcanoes, aftershock zones, and other natural laboratories for key lithosphere-scale processes on land and in the ocean). IRIS PASSCAL, EarthScope Transportable Array and Flexible Array instruments, Ocean Bottom Seismometer Instrumentation Pool (OBSIP), and *Marcus G. Langseth* research vessel all presently provide key seismic data for such studies. After being archived in perpetuity in a community data center, such as the IRIS DMC, these data from temporary deployments and expeditions become part of the global seismic data resource and are increasingly re-exploited for research topics that range far beyond the original motivations. Although improved seismic instrumentation of the ocean environments will be achieved by the NSF Ocean Observatories Initiative (OOI), its current seismological component has become very limited, and there is generally a dire need for much more extensive coverage of ocean environments using subsurface borehole seismometer deployments and an expanded pool of broadband OBSs. Systematic deployment of broadband OBSs in targeted areas of the oceans holds great promise

for scientific breakthroughs, such as those proposed in the Ocean Mantle Dynamics Science Plan (2000) produced by the NSF-funded community. The controlled-source community has expressed a need for increased numbers of three-component instruments to enable dense deployments that are not possible with current instrument pools and to exploit the full seismic wavefield in these studies.

RECOMMENDATIONS

- Continue support by federal agencies to sustain seismic data collection and open data distribution facilities with long-term amortization and investments in new technologies.
- Increase the pool of three-component broadband sensors, which are required for improved resolution in next-generation 3D and 4D imaging efforts of crustal, lithospheric, and deep mantle and core structure.
- Support the EarthScope Transportable Array deployment through completion of its traverse across the United States, including Alaska.
- Expand the pool of portable OBSs for systematic large-scale deployments in portable arrays.
- Significantly increase the number of sensors for active-source experiments, including three-component systems, which are essential for advances to occur in high-resolution crustal imaging.

CONTROLLED SEISMIC SOURCE SUPPORT

The highest-resolution imaging of the near-surface crust requires densely distributed controlled seismic sources recorded by dense receiver arrays. The NSF-funded research vessel *Marcus G. Langseth*, which has a large airgun array and four 6-km streamers of dense hydrophones, has recently greatly enhanced community research capabilities in marine geologic studies. In contrast, the land-based community has no such

shared-source facility. The cost of controlled sources has become a limiting factor in the funding of research grants from NSF and other sources. This paucity of funding has led to a reduction in the number of projects and a widening gap between academic and industry capabilities in this critical and workforce-challenged field. Improved and sustained availability of sources to the research community is thus required to underpin

scientific advances, to broaden the pool of academic groups conducting such work, to advance partnership opportunities with industry, and to enhance core educational opportunities for Earth science students.

The vibrator trucks of the Network for Earthquake Engineering Simulation (NEES) facility could be made more available for seismological research on very shallow structure, which may require increased flexibility in the current operation of this facility. NEES vibrators lack sufficient capabilities for crustal-scale imaging. The controlled-source seismic imaging efforts of the USGS have substantially diminished over the past several decades, and there is no longer a dedicated internal program to collaborate with universities in the permitting and handling of buried explosive sources, which requires highly specialized expertise and is facilitated by government participation. Drilling shot holes for explosives and vibrator truck arrays can both be subcontracted commercially, but the substantial cost is a significant impediment to most researchers and current research program budgets. Establishing a broad-based community source

facility, including drill rigs, explosive-handling capability, and a vibrator array, and integrating the needs and resources of IRIS, USGS, and NEES, would sustain the health of active seismic imaging at all scales. This facility could work on a model similar to DOSECC, which provides scientific drilling rigs, combined with expertise for the contract hiring of industry rigs where appropriate and cost effective.

RECOMMENDATIONS

- Establish a facility or collection of facilities for sources used in active-source seismology so that research programs and education in this area can be sustained. This facility could possibly be developed through access to the vibrator trucks of NEES, reinvigorated participation of the USGS in active-source seismology, and in partnership with industry.
- Improve interactions among academic, governmental, and industrial efforts in active-source seismology to sustain the discipline.
- Expand the ability to conduct 3D active-source imaging at sea.

PRODUCING ADVANCED SEISMOLOGICAL DATA PRODUCTS

The diverse applications of seismology for basic research and environmental monitoring all benefit from the long-standing efforts to produce catalogs of earthquake parameters (location, origin time, magnitude) and mathematical representations of Earth structure (1D, 2D, and 3D seismic velocity and density distributions). Seismic source catalogs and models are used widely beyond seismology, extending the disciplinary impact to earthquake engineering, earthquake insurance, geotechnical, geological, and geochemical arenas. Indeed, the principal seismic data for most of these communities are earthquake catalogs rather than seismograms. It is incumbent upon the discipline to provide the most reliable and comprehensive compilations of seismological knowledge

to all users. However, the distributed nature of the many efforts that produce earthquake parameter lists and Earth models on various scales leads to an array of products that lack clear authoritative validation and easy access. The widespread use of the 1D Preliminary Reference Earth Model (PREM), produced in 1981, clearly demonstrates the importance of well-defined syntheses of seismological knowledge.

Recent advances in data quality and availability, advanced processing methods, and computational capabilities enable significant improvements in earthquake catalogs and Earth models, yet there is not a dedicated effort to systematically enhance these fundamental seismological products. It is realistic to commit

to monitoring almost all seismicity on all continents down to magnitude ~ 3 events, and beneath the oceans down to magnitude ~ 4, over the next decade. Event location accuracy can be systematically improved on large and even global scales, with relative locations as accurate as a few hundred meters rather than current levels of a few to tens of kilometers. Integration of catalogs from various seismic systems into an authoritative, readily accessible global seismic source database would benefit basic research, applied research, and many societal applications that use seismicity distributions. It is also realistic to commit to developing a consensus 3D Earth model as a reference structure for diverse applications. This is a very complex undertaking and should be coordinated at the agency level, with an understanding that models evolve and require updating as data and methods improve.

Natural disasters provide both learning and teaching opportunities that can be exploited if infrastructure is in place in advance. Rapid responses to exploit the window of opportunity for making critical transient observations (e.g., fault-zone drilling, hydrological monitoring, aftershock recording, volcanic deformations) must be planned in advance. Rapid dissemina-tion of seismological information to educators, emergency response coordinators and the general public also requires in-place infrastructure.

RECOMMENDATIONS

- Integrate regional and global seismic bulletins into an openly available, definitive international seismic source catalog.
- Commit to improving earthquake location accuracies on large scales by using advanced processing methods and strive to complete catalogs down to levels of magnitude 3 in continents and 4 in oceanic regions.
- Develop a 3D Earth model as the next generation community model beyond PREM, describing the anelastic, anisotropic, aspherical Earth structure by standardized parameterization that can be used by multiple disciplines.
- Provide ready access to products of seismological research in forms that are useful to fellow Earth scientists to facilitate dissemination of seismological knowledge.
- Expand infrastructure for learning from disasters and mounting scientific response, along with improved outreach with information for the public.

ENHANCING FREE AND OPEN ACCESS TO DATA

Seismology is an intrinsically global and international undertaking, and it relies upon strong coordination and cooperation among governments, international organizations, and universities. Seismological contributions are greatly served by global open access to real-time seismic data from all international data-collection activities, building on the examples of the USGS NEIC, IRIS DMC, and FDSN-participant data centers, along with many U.S. university programs. Efforts to provide access to data that are not now freely available, such as the IMS seismic recordings, thousands of instruments in national regional recording systems, and other currently restricted seismic data sets, will enhance multi-use of the corresponding signals for investigating important topics in the Earth system. Global concerns about earthquake hazards, environmental change, and nuclear testing present many opportunities for international partnerships and interactions on technology transfer, capacity-building, confidence-building, and integrative hazard assessment that are all complemented by basic research. The advanced state-of-the-art of seismology in the developed world can be leveraged to enfranchise and bolster progress in developing nations that are struggling to deal with challenging hazard issues and limited resources.

- Continue to have federal programs and seismology organizations strongly advocate for open access to seismic data on a global basis, with real-time access to the greatest extent possible.

- Communicate and foster seismological capabilities for addressing hazards and environmental monitoring concerns and data exchange with developing nations through coordinated international efforts.

ENHANCED INTERDISCIPLINARY COORDINATION

Progress on the Seismological Grand Challenges listed in this long-range plan and the many societal applications of seismology hinges on improved interdisciplinary interactions and communications. Strong synergisms exist within the Earth science arena between seismology and other disciplines, such as geodesy, geodynamics, mineral physics, geology, and geochemistry. These connections are fostered by professional societies such as the American Geophysical Union (AGU), the Society of Exploration Geophysicists (SEG), and the International Association for Seismology and Physics of Earth's Interior (IASPEI). Research coordination is abetted by NSF-funded community organizations and consortia such as IRIS, the Southern California Earthquake Center (SCEC), the Cooperative Institute for Deep Earth Research (CIDER), the Consortium for Materials Properties Research in Earth Sciences (COMPRES), and the geodetic consortium UNAVCO. NSF programs such as EarthScope, MARGINS, RIDGE, and CSEDI also enhance multidisciplinary communications. Coordination with the National Ecological Observatory Network (NEON) can augment societal applications of seismology. The United States has only limited ties between industry and academia for workforce training and technology development in active-source seismology. Many of the novel seismological areas of research identified in this document, including some aspects of atmospheric, climate, and ocean research, are at early stages in building constructive coordination among science communities, funding agencies, and industry.

RECOMMENDATIONS

- Sustain multidisciplinary integration efforts and foster improved communications and coordination on seismology activities among NSF divisions of Earth Sciences, Ocean Sciences, and Atmospheric Sciences, and the Office of Polar Programs. Overcome existing institutional barriers to optimal cross-divisional seismology activities through coordination at the Geoscience Directorate level of NSF.

- Encourage federal and state agencies, universities, and scientific organizations to support interdisciplinary workshops on critical interfaces in the shallow Earth system, extreme environments, deep Earth processes, and environmental change with active participation by seismologists.

ADVANCES IN INSTRUMENTATION

Technological advances permeate the discipline of seismology, which has been a scientific leader in embracing advances in computer storage, digital processing, telecommunications, Internet dissemination of information, and other technologies. Specific to the discipline are needs for further advances in seismic sensors and high-resolution data acquisition. The current sensors for recording very broadband (VBB)

seismic data at the long-period end of seismic ground motions (Streckeisen STS-1 sensors deployed in many seismic networks) are no longer being produced and will need replacement as they age. Development of a next-generation VBB sensor is a high priority, and is required to ensure on-scale, complete recordings of the very largest earthquakes, such as the 2004 Sumatra tsunami earthquake, and to record with high fidelity Earth's free oscillations, slow earthquake motions, and very-long-period "noise" arising from oceanic, atmospheric, and other sources. New micro-electro mechanical systems (MEMS) are being designed to sense short-period ground vibrations, and further development of this technology may soon enable vast increases in numbers of inexpensive sensors that can provide high-density sampling of ground motions in urban and remote areas. Extension of the usable period band for MEMS or other novel low-cost sensors to the range of tens of seconds would usher in a revolution in seismic tomography of the deep Earth by facilitating 3D and 4D crust and mantle imaging experiments using orders of magnitude more receivers than are fieldable with current (e.g., IRIS PASSCAL) seismometer technology. New seismic sensors for hostile environments (extreme cold, ocean bottom, deep boreholes, and extraterrestrial environments) are critical for expanding the scientific reach of seismology and for addressing the discipline's Grand Challenges. University participation in seismic instrumentation development has diminished over time, and sustaining specialized expertise in ground-motion measurement technologies is a challenge that confronts the discipline.

RECOMMENDATIONS

- Encourage collaborations across federal agencies that utilize very broadband seismic data for monitoring purposes to support development of next-generation very broadband seismometers to replace current instruments.
- Explore MEMS technologies to develop low-cost seismic sensors that can be deployed in great numbers and can supplement or replace current seismometers.
- Increase the number of strong motion instruments near faults and in urban areas to improve constraints on rupture processes and to better understand the relationship between ground motion and building damage.
- Continue to develop next-generation telemetered seismic instrumentation in hostile environments (e.g., volcanoes, glaciers, seafloor).
- Develop partnerships among industry, national laboratories, academia, and federal agencies to advance and sustain seismic instrumentation innovation and capabilities.
- Sustain existing permanent networks, such as the GSN and ANSS, as long-term observational systems for both research and monitoring, through stable funding from multi-agency partners and continued upgrades to improve reliability and efficiency.

SUMMARY

Seismology is an exciting, vigorous, and important discipline, with broad relevance to major challenges confronting society, including environmental change, coping with natural hazards, energy resource development, and national security. Seismology provides the highest-resolution probes of inaccessible regions of Earth's interior from shallow crustal sediments to the central core, and thus plays a primary role in efforts to understand the structure and dynamics of Earth's many internal systems. The discipline has grown to its current prominence by sustained federal support of basic research, which ensures training of new generations of seismologists via university research programs, along with technical developments that enhance applied research in nuclear monitoring, exploration and resource management seismology, earthquake and volcano hazard monitoring, and environmental change evaluation.

Looking to the next 10 to 20 years, the seismological community has herein defined 10 Grand Challenge basic research questions where seismology offers the opportunity for fundamental contributions. These topics all address Earth systems that can be probed and quantified using seismological techniques. This document identifies scientific challenges and opportunities for basic research in seismology to be supported by federal, university, state, and industry programs. It is hoped that this document will usefully inform and inspire program managers and agency directors to help advance and sustain the critical infrastructure, workforce, and scientific capabilities necessary for the field to fully realize its potential contributions to science and to society at large.

APPENDIX
KEY SEISMOLOGICAL PRACTICES

Seismological approaches to solving the Grand Challenges described in this document include a plethora of analysis techniques and distinct seismic wave analyses. Underlying all of the methods are some intrinsic attributes of the discipline that warrant discussion. These include the practices of monitoring Earth's natural and human-made sources, and the practices of imaging Earth's systems and modeling the ground shaking using the resulting Earth models.

MONITORING DYNAMIC PROCESSES IN EARTH'S ENVIRONMENT

Earthquakes, volcanoes, ocean storms, glacial flows, and many other natural sources are located, identified, and quantified through fundamental monitoring practices of seismology. These practices require long-term operation of many seismometers in arrays and networks of various scales with continuous data telemetry. Monitoring operations include sparse global seismographic networks with very broadband recording capabilities, dense regional networks with high-resolution capabilities, and temporary deployments in remote areas such as Antarctica, the ocean, mountain ranges, and dense jungles. Commitment to long-term operations for monitoring natural hazards is essential, but long-term monitoring is also crucial for investigating relatively slow Earth processes, such as changes associated with global warming, inner core super-rotation, and many other seismically observable phenomena. Open access to the seismic data collected

for monitoring purposes ensures full exploitation of the signals for multi-use purposes of basic research and diverse monitoring functions.

More than 200,000 earthquakes are located each year. Continuous seismic monitoring provides the where and when of earthquakes and can guide emergency response activities, and the same data provide information needed to understand the physics of earthquake ruptures. Continuous monitoring has allowed the discovery of new kinds of seismic phenomena, such as the seismic tremor discussed above, which may help future hazard reduction efforts. Seismic monitoring of earthquakes also provides critical information about site responses, which is essential for earthquake engineering. Shallow geological heterogeneity produces profound variations in surface ground shaking, and empirical calibration remains the best approach to

calibrating these effects. Nonlinear ground response to strong shaking and complex interaction of waves that travel through the extreme 3D heterogeneity found in near-surface structure can only be quantified with databases accumulated over long monitoring intervals.

Continuous operation of seismic stations, and real-time processing of the recorded data underlies capabilities such as real-time warning systems for earthquakes and tsunamis. Volcanic eruption warning systems also rely on the seismic monitoring approach, as it can sense both seismicity accompanying magma motions and changes in the volcanic plumbing system. Exotic events such as bolide impacts, glacial surges and calving, and other dynamic sources are captured by the same monitoring systems used for earthquake and volcano monitoring. Similarly, nuclear test monitoring uses the same monitoring approaches as for other phenomena, and signals from quarry blasts, mine bursts, and human sources, such as the collapse of the World Trade Center towers and implosion of the Russian submarine, Kursk, have been studied using seismic waves obtained from global monitoring systems. Although serendipitous, it is the very act of sustained seismic monitoring of the Earth system that has allowed these phenomena to be studied. Many applied areas of monitoring have developed, such as for reservoir management, hazardous waste injection, and mine safety, and dense networks of seismometers are involved in every case.

All seismic monitoring applications can be enhanced by increasing the number of stations. Japan has led the world by deploying the densest networks of
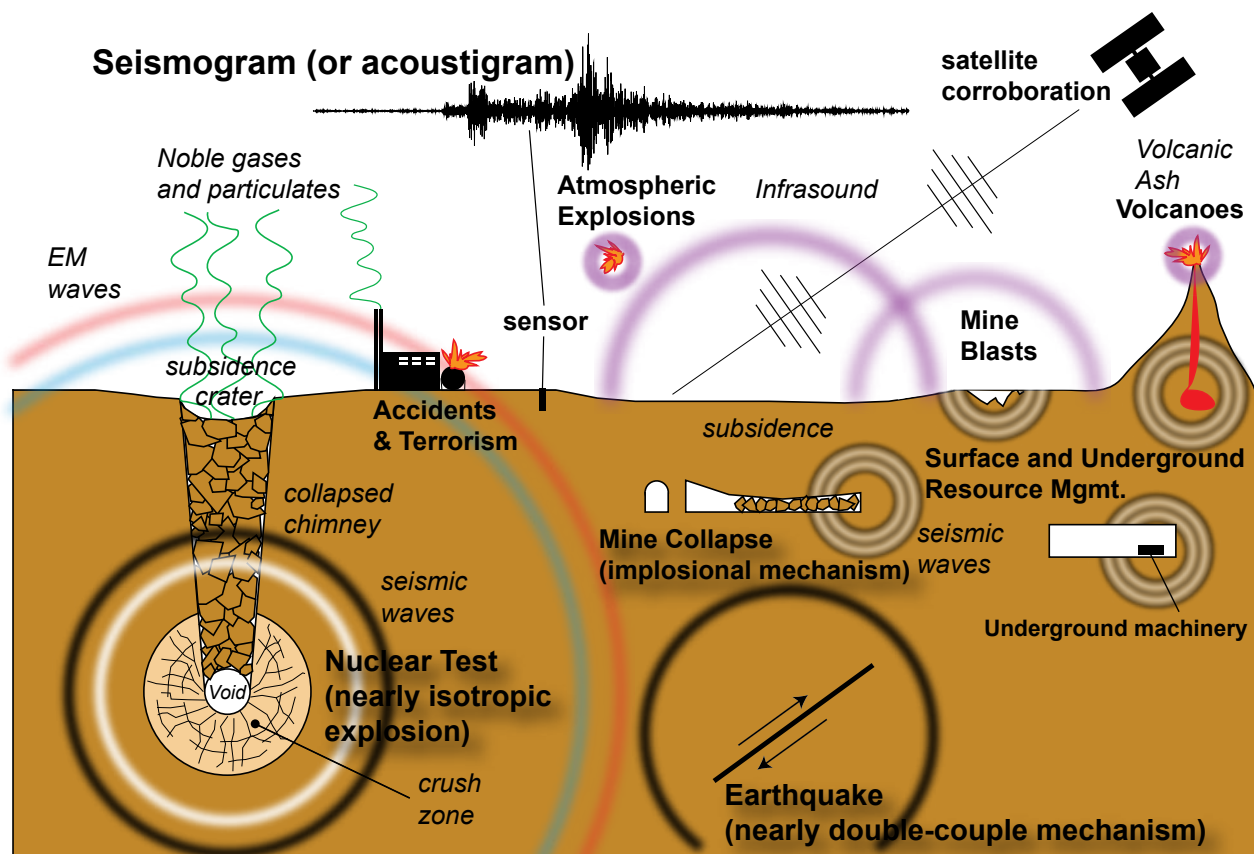
Schematic view of the Earth monitoring environment. Energetic processes in the atmosphere, solid Earth, and hydrosphere (not shown) create seismic and acoustic waves that are readily detected with sensor networks, and frequently form a core component of multidisciplinary monitoring efforts. (Image courtesy of W. Walter and D. Harris.)

seismic instruments of very high quality, prompted by an immense exposure to earthquake hazards across the entire country. There is a significant demand for increased numbers of inexpensive and easily deployed sensors for blanketing urban areas to assess local site response variations and for high-resolution studies of shallow crustal structure. Global observatories require new generations of very broadband instrumentation to record all ground motions from future great earthquakes so that rapid faulting assessments and tsunami-potential assessments can be made. Robust portable sensors in great numbers are needed for deployments to monitor aftershock sequences and to study transient phenomena in polar environments, volcanic environments, and other areas that are only sparsely monitored by permanent stations.
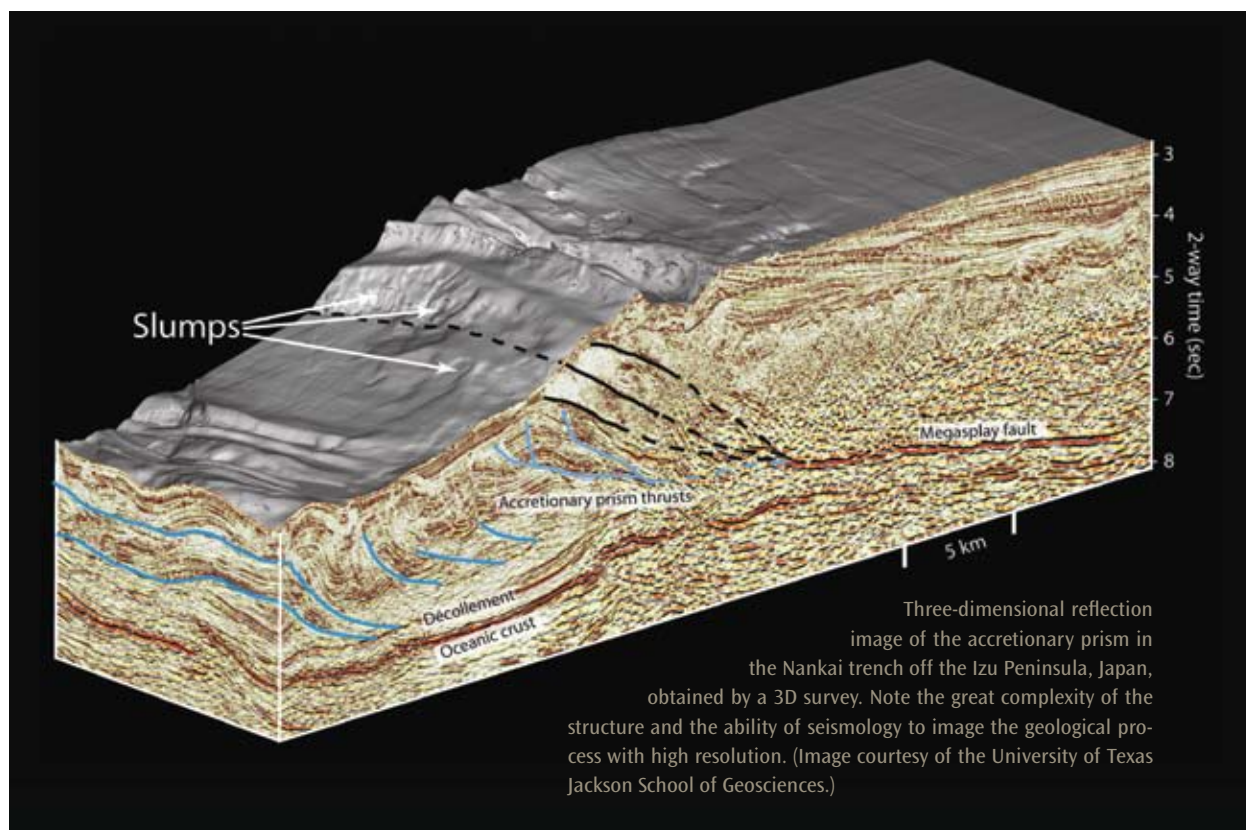
Extending monitoring into ocean-bottom environments is an important priority for the future. Most earthquakes occur at ocean trenches, and tsunamis pose an additional marine hazard. It is also impossible to uniformly monitor Earth's activities and to understand its global dynamics through seismic imaging when 70% of its surface is off limits. This issue will require additional research into the development of reliable and inexpensive broadband OBS and oceanic borehole instruments, and methods for their cost-effective low-noise installation.

Seismic monitoring is an international undertaking, and all countries have some monitoring needs. Coordination and seismic data sharing among national efforts is clearly of benefit to all monitoring efforts. Continued U.S. advocacy of open, real-time data access to monitoring networks is a top priority.

MULTISCALE 3D AND 4D IMAGING AND MODELING OF COMPLEX EARTH SYSTEMS

All of the Seismological Grand Challenges involve high-resolution determination of source and/or structural properties by seismic wave analysis. The essence of this practice is the solution of wave-propagation equations to resolve 3D structural interactions or source excitations. Source imaging is explicitly time-dependent and repeated structural imaging can also be 4D, with time-dependent changes in the medium being sensed. When complex representations of sources and the medium are obtained, calculation of seismic responses for new geometries can be used to predict shaking variations by forward modeling. Imaging and modeling are coupled and comprise key attributes of the discipline with specific data and computational needs.

Various programs now routinely process long-period signals to determine earthquake source parameters that describe source size, earthquake fault orientations and slip directions, and other fundamental properties. The resulting earthquake solutions are used for tectonic studies, as starting points for more detailed rupture investigations for large events, and for earthquake hazard assessments. Less-routine determinations of finite-source models for large events describe the spread of slip over the fault during an earthquake, with the added information about the rupture being useful for studies of frictional variations, hazard analysis, aftershock analysis and rupture mechanics. Expanded coverage of Earth's surface, particularly in the ocean, can greatly abet this detailed source imaging, mainly

Slumps

Megasplay fault

Accretionary prism thrusts

5 km

Décollement

Oceanic crust

2-way time (sec)
3 4 5 6 7 8

Three-dimensional reflection image of the accretionary prism in the Nankai trench off the Izu Peninsula, Japan, obtained by a 3D survey. Note the great complexity of the structure and the ability of seismology to image the geological process with high resolution. (Image courtesy of the University of Texas Jackson School of Geosciences.)

for very large earthquakes; this science was one of the original motivations for deploying more permanent ocean seismic observatories. Resolution of detailed rupture processes is delimited by the accuracy of the structural models, so those must also improve.

Imaging methods also underlie all determinations of Earth structure. With the basic spherically symmetric Earth structure having been determined by the 1980s, seismologists subsequently turned their attention to resolving lateral variations in seismic wave speeds using data from regional and global seismographic networks. This use of data created the still-booming field of seismic tomography, the seismological equivalent of medical CAT-scan imaging, by which models for heterogeneous P-wave and S-wave structure of the crust, mantle, and core have been determined. Global images are variable in resolution due to the nonuniform distributions of sources and receivers, and significant improvements in models are driven primarily by

new data-collection efforts in previously unsampled areas or with densified station spacing. Imaging oceanic crust and upper mantle structure continues to be particularly hampered by a lack of oceanic stations, and there continues to be a pressing need for deployment of a global ocean bottom seismographic network.

Seismic tomography is moving toward "finite-frequency" imaging, in which the full bandwidth of seismic signals is harnessed to probe different aspects of Earth structure. In addition, efforts have commenced to map anelastic attenuation structure and anisotropic structure on regional and global scales using complete waveform information. These efforts will provide improved constraints on thermal and compositional structure and deformational processes in the interior.

State-of-the-art practices in exploration seismology for 3D and 4D imaging involves acquisition, processing, and interpretation of huge seismic data sets. The

Okmok volcano V_s model
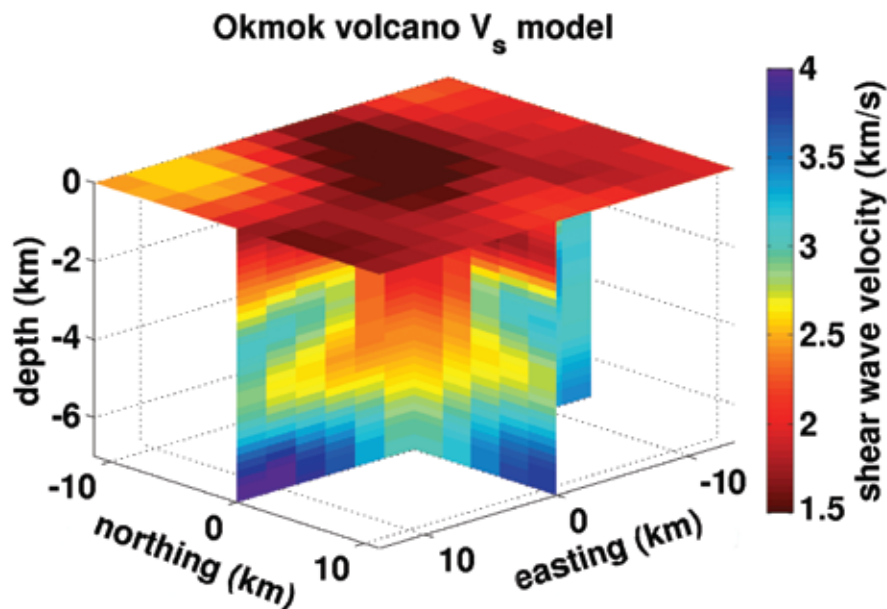
Slices from a 3D image of Okmok Volcano, Alaska, constructed from continuous recordings of ocean noise. Okmok is one of the most active volcanoes in the Aleutian island chain and poses a threat to aviation in the heavily used north Pacific air-traffic corridors. The 3D image is centered on the main axis of the volcano. Independent GPS, InSAR, and petrologic data further support the presence of a shallow magma chamber at Okmok. (Image courtesy of M. Haney.)

current targets of 3D imaging are very complex subsurface structures that require improved wavefield migration and modeling techniques. The goal of 4D imaging is to monitor changes in reservoirs due to oil and gas extraction and/or the injection of gas or water by comparing repeated datasets. Using the same philosophy, scientists practicing crustal-scale seismology now perform repeated applications of noise cross-correlation tomography in a geographical area of interest to reveal subtle changes in seismic wave speeds related to fluid flow, fault-zone healing, or magma migration.

The development of increasingly sophisticated 3D models of Earth's interior has led to a need for rapid, accurate simulations of seismic wave propagation in multiscale media. Taking advantage of modern numerical algorithms and large parallel computers, seismologists are now calculating fully 3D synthetic seismograms in complex 3D anelastic, anisotropic Earth models for forward modeling long-period (> 5 s) ground motions. A current challenge lies in harnessing these numerical capabilities to enhance the quality of the 3D models, in conjunction with improving models of source rupture processes. Strategies for

addressing this formidable imaging problem are being explored, and are driving seismology's computational demands. For a typical regional or global dataset, complete waveform tomography methods may involve thousands of 3D simulations and hundreds of thousands of CPU hours, requiring convenient access to large computational resources.

To image smaller-scale features than resolved by current global tomography, such as the detailed structure of mid-oceanic ridges and subduction zones, ultra-low velocity zones and anisotropy just above the core-mantle boundary, the morphology of plumes, and the structure of the inner core, there is need to accurately model 3D wave propagation at short periods (< 5 s) over long distances. Currently, we can only compute short-period solutions for simple spherically symmetric Earth models, but the advent of petascale computing (capable of greater than 10^{15} floating point operations per second) will enable simulations for 3D Earth models in the near future. It is critical to ensure that the solid Earth science community has access to the necessary computer resources.

RECOMMENDED READING

American Geological Institute, Geoscience Workforce Age Distribution, Geoscience Currents, No. 16, http://www.agiweb.org/workforce, 9 October 2008.

Basic Research Opportunities in Earth Sciences, 2001. National Research Council, National Academies Press, Washington, D.C. (http://books.nap.edu/catalog php?record_id=9981)

Cooperative Studies of the Earth's Deep Interior: Development, Discoveries, Future, 2004. CSEDI, 42 pp. (http://www.csedi.org/)

Critical Needs for the Twenty First Century: The Role of the Geosciences, 2008. The American Geological Institute. (http://www.agiweb.org/gap/trans08.html)

Current and Future Research Directions in High-Pressure Mineral Physics, 2004. COMPRES, ESS Building, Stony Brook, NY 11794. (http://www.compres.stonybrook.edu/Publications/index.html)

Earthquake Risk Reduction: Addressing the Unmet Challenges, 2008. Earthquake Engineering Research Institute, 32 pp. (http://www.eeri.org/cds_publications/catalog/product_info.php?products_id=291)

Geosciences: The Future, 2007. International Union of Geodesy and Geophysics, 106 pp. (http://www.iugg.org/publications/reports/)

Grand Challenges for Disaster Reduction, 2005. National Science and Technology Council Subcomiittee on Disaster Reduction, 21 pp. (http://www.nehrp.gov/pdf/grandchallenges.pdf)

Living on an Active Earth, 2003. National Research Council, National Academies Press, Washington, D.C.

Ocean Mantle Dynamics Science Plan, 2000. National Science Foundation, Washington, DC. 43 pp.

Origin and Evolution of Earth: Research Questions for a Changing Planet, 2008. National Research Council, National Academies Press, Washington, D.C. (http://www.nap.edu/catalog.php?record_id=12161)

Securing Society Against Catastrophic Earthquake Losses, 2003. Earthquake Engineering Research Institute, 62 pp. (http://www.eeri.org/cds_publications/catalog/product_info.php?products_id=230)

ACRONYMS AND TITLES

AGU – American Geophysical Union

ANSS – Advanced National Seismic System, operated by the USGS

ATM – Atmospheric Sciences Division of the NSF

CIG – Computational Infrastructure for Geodynamics, funded by NSF

CIDER – Cooperative Institute for Deep Earth Research

CISN – California Integrated Seismic Network

COMPRES – Consortium for Materials Properties Research in Earth Sciences

CSEDI – Cooperative Studies of the Earth's Deep Interior, funded by NSF

CTBTO – Comprehensive (Nuclear) Test Ban Treaty Organization

DMS – IRIS Data Management System

DoD – Department of Defense

DOE – Department of Energy

DOSECC – Drilling, Observation and Sampling of the Earth's Continental Crust

EAR – Earth Sciences Division of NSF

EarthScope – NSF/USGS/NASA Major equipment facility for studying the North American continent

EERI – Earthquake Engineering Research Institute

FDSN – International Federation of Digital Seismograph Networks

FEMA – Federal Emergency Management Agency

GEO – Geosciences Directorate of NSF

GEOSS – Global Earth Observation System of Systems

GPS – Global Positioning System

GSN – Global Seismographic Network

IASPEI – International Association for Seismology and Physics of Earth's Interior

IAVCEI – International Association for Volcanology and Chemistry of Earth's Interior

IMS – International Monitoring System of the CTBTO

IODP – Integrated Ocean Drilling Program

ION – International Ocean Network

ISC – International Seismological Centre

InSAR – Interferometric Synthetic Aperture Radar

IRIS – Incorporated Research Institutions for Seismology

IUGG – International Union for Geodesy and Geodynamics

MARGINS – Continental margins program, funded by NSF

MELT – Mantle Electromagnetic and Tomography experiment

NASA – National Aeronautics and Space Administration

NEES – Network for Earthquake Engineering Simulation, funded by NSF

NEIC – National Earthquake Information Center, operated by the USGS

NEON – National Ecological Observatory Network, funded by NSF

NOAA – National Oceanic and Atmospheric Administration

NSF – National Science Foundation

NVEWS – National Volcano Early Warning System of the USGS

OBS – Ocean Bottom Seismometer

OBSIP – Ocean Bottom Seismometer Instrumentation Pool, funded by NSF

OCE – Ocean Sciences Division of the National Science Foundation

OOI – Ocean Observatories Initiative, funded by NSF

OPP – Office of Polar Programs of NSF

PASSCAL – IRIS Program for Array Seismic Studies of the Continental Lithosphere

PBO – Plate Boundary Observatory, a component of EarthScope

PGA – Peak Ground Acceleration

PREM – Preliminary Reference Earth Model

RESESS – Research Experience for Solid Earth Science for Students internship program

RIDGE – Ocean ridge research program, funded by NSF

SAFOD – San Andreas Fault Observatory at Depth, a component of EarthScope

SAGE – Summer of Applied Geophysical Experience

SCEC – Southern California Earthquake Center

SEG – Society of Exploration Geophysicists

SOARS – Significant Opportunities in Atmospheric Research and Science UCAR internship program

SSA – Seismological Society of America

TeraGrid – An open scientific computational resource infrastructure funded by NSF and partners

UCAR – University Corporation for Atmospheric Research

UNAVCO – University consortium for measurement of crustal deformation

USArray – Seismographic component of EarthScope

USGS – United States Geological Survey

WWSSN – World-Wide Standardized Seismographic Network

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