Seismological Grand Challenges in Understanding Earth’s Dynamic Systems
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Executive Summary

Seismology 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 most 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 the active wave sources and to determine structures and processes at all depths in the planetary interior at higher resolution than is possible by any other approach, revealing both present-day and multi-billion-year-old dynamic events. Recent breakthroughs in theory and data processing now allow every byte of continuous seismological data acquired to be used for imaging sources and structures in the dynamic system, 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 directly 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 internal wave sources and structure. Seismology plays central roles in hydrocarbon and resource exploration, earthquake detection and quantification, volcanic-eruption and tsunami-warning systems, nuclear test monitoring and treaty verification, aquifer characterization, earthquake hazard assessment
and strong ground motion prediction for the built infrastructure, including lifelines and critical facilities. 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 decade or two and defined the following 10 Seismological Grand Challenge research questions:

- How do faults slip?
- What is the relationship between stress and strain in the lithosphere?
- How do processes in the ocean and atmosphere couple to the solid Earth?
- How does the near-surface environment affect resources and natural hazards?
- 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) Multi-scale 3D and 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 ten Grand Challenge questions requires sustained and expanded support of seismic data acquisition, archival, and distribution facilities. Global and regional seismological observatories 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 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 between 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 should be promoted, with active seismological participation.

Many of the government and private sector users of seismology are now confronted with serious workforce issues. Expanded efforts to attract quantitatively oriented, diverse graduate students to the discipline are required. These efforts should be abetted by building on current education and outreach endeavors of the seismological community, and by developing stronger partnerships between academic, industry, and government laboratories impacted by the workforce issue.
Seismology holds great promise for achieving major new 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 the basic research programs and infrastructure for this burgeoning geophysical discipline. With the well-established practices of open data sharing 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 rare occasions, 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, producing propagating disturbances that expand outward from the energy source through the surrounding rocks as 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 theoreticians drew upon solid mechanics and elasticity to develop deep understanding of elastic waves. Thus commenced 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 numerous 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 to study both the dynamic sources of the seismic waves and the characteristics of the rocks through which they travel along with myriad industrial, societal and scientific subfields.

Placing ground motion sensors, or seismometers, on Earth’s surface is akin to putting stethoscopes on the Earth system and listening for the internal rumblings and gurglings of the planet’s internal processes. Over the past century, seismologists have learned to unravel the rich information contained in seismograms, applying quantitative elastic wave theory to accumulating databases and distilling meaningful information from the cacophony of seismic motions. Classic seismological applications include 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 mature and 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 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 essential 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 signals by many government agencies and research programs produces rapid bulletins of global seismic sources and prompt information for disaster mitigation as essential aspects of continuous monitoring of the Earth system. Large-scale deployments of land- and sea-based instruments utilize both active human-made sources and passive natural sources of seismic waves, revealing multi-scale 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 size and 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.
A defining attribute of seismograms is that they are simply records of ground motion as 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. Studying the diverse Earth systems requires globally distributed sensors and international collaborations on data acquisition and exchange. The multi-use attribute of seismic signals places great premium on continuously recording ground motions over as wide as possible frequency band, 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 Seismographic 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), near real-time access to seismic data is also of great importance; whenever it is possible to transmit the ground motion data to open archives in real time, multiple societal applications of the signals are enabled.

By its very nature, seismology is intrinsically sensitive to many active, dynamic processes happening today in Earth’s dynamic systems, and the discipline has expanded its scope to sensing and characterizing numerous aspects of environmental change and near-surface processes, including ground-water conditions, glacial motions, storm migration, the ocean wave environment, and oceanic circulation. Much of modern earth science research addresses complex physical systems that involve interfaces among multiple disciplines, 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 an alphabet soup of research community organizations (CIDER, COMPRES, CSEDI,
FDSN, IASPEI, IAVCEI, IRIS, Margins, RIDGE, SCEC, UNAVCO – all 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, and atmospheric sciences.

This centrality of seismology in earth science and monitoring engages multiple U.S. federal agencies in supporting the discipline, including the 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, politically influential roles.
The cumulative volume of seismic data archived at the IRIS Data Management Center (top) for major seismic networks totals 81.3 terabytes as of August 2008. The annual number of terabytes shipped from the IRIS DMC (bottom) 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).

One sign of a healthy scientific enterprise is that it is producing major advances and paradigm shifts in the field. 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 on-line 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.

- The discovery of coherent information contained in recorded seismic “noise” allows every data byte to be used for scientific application; entirely new approaches to structural studies and investigations of changes in the environment have emerged. The background vibrations of the Earth contain information about sources and structures that was not recognized until recently.

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 USA stations including the EarthScope USArray Transportable Array and regional seismic networks, inter-station empirical Green's functions for all available station pairs were recovered and inverted for regional seismic velocity structure. Thick black lines define
the major tectonic boundaries in the region. (Image courtesy of M. P. Moschetti, M. H. Ritzwoller, and N. M. Shapiro).

The 2001 Kokoxili (Mw 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 which continued for at least 290 km 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 super-shear velocities) to “slow earthquakes” that involve anomalously slow ruptures - some so slow that the fault sliding does not even radiate detectable seismic waves - has
unified seismic and geodetic monitoring of fault zones and has provided significant new insights into frictional sliding and earthquake hazard.

Properties of a recent 3D S-wave velocity earth model showing (a) the power spectrum of velocity variations as a function of wavenumber 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-scale (angular degree 2) patterns dominate at both of these depths, 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 indicates importance of thermo-chemical convections in the mantle (Image courtesy of B. Kustowski, G. Ekström and A. Dziewonski).
• The discovery of predominance of large-scale structures 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 coordinated by the NSF, is providing unprecedented spatial coverage of seismic and geodetic observations across North America, revealing remarkable crustal and lithospheric 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 great 2004 Sumatra earthquake-generated tsunami 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 in the future.
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).

The continued health and vigor of seismology requires federal and industry attention to critical foundations of the discipline. 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 associated infrastructure needs essential for making progress on these topics.
Grand Challenges for Seismology

The history of seismological advances has validated the approach of sustaining diverse seismological basic science research as the most effective way of developing and enhancing the societally critical applications of the discipline. This strategy ensures workforce 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 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 tends to associate seismology 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, holding many implications for society. The relentless relative motions of Earth’s plates concentrate stresses that are relieved mainly as slippage along faults on plate boundaries and within their interiors. Multi-scale fault zone systems are involved in earthquake initiation, rupture and termination, and 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 behavior. The most spectacular releases of stress occur in conventional earthquakes. Potential energy stored up in the rock over hundreds to thousands of years, as a result of adjacent relative plate motions rapidly releases as fault frictional resistance is overcome; 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 huge ground motions.

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

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. Variations of fluid concentrations along fault zones are likely to play important roles in frictional behavior, and some 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 replicating earthquakes recurring at the same location on a fault have been studied. Global and regional arrays of seismic stations 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 sciences 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 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 basic understanding of how and where faults are likely to fail, but there is currently lack of reliable short-term warnings of an impending event. The insights gained have provided useful seismic hazard assessments for land-use planning, as guidance for construction standards, and for planning for emergency response. But there is no question that far more can be achieved by enhancing our fundamental 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 the diverse types of fault sliding?
- 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 is friction different for high-speed slip?
- What is the fundamental nature of asperities and the cause of friction variations?
- How is episodic tremor and slip related to large earthquake occurrence?
- How do rupture zones recover and reload?
- How do large and small earthquakes differ, if they do?
- Can rupture directions be anticipated based on material properties?
- What is the fractal nature 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 the built environment?
• How quickly can the size of an fault slip event be determined and reliable shaking and tsunami warnings issued?

Seismological Approaches and Requirements to Make Progress
• Seismic arrays of boreholes near faults.
• Pools of instruments for rapid deployment after earthquakes.
• Strong ground motion recordings for more large earthquakes.
• Sustained long-term operation of global and regional networks.
• Real time analysis of finite-faulting properties for rapid earthquake and tsunami warning systems.
• Increase communications with other disciplines studying earthquake science.

SIDEBAR #1

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, and the International Seismological Center (ISC), and many international organizations are extensively used for seismic hazard analysis as well as basic research applications. The map on the left shows locations of 81,679 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. 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 events tend to concentrate along faults that are extensively creeping. This observation suggests that tiny patches 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, JGR, 113, B08311, 2008)

SIDEBAR #2

**Earthquake Rapid Warning Systems**

Before the next 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 meter lights could turn red. Nuclear power plants could lower their control rods while refineries isolate tanks and vulnerable pipelines. The idea is to combine modern digital seismic networks with modern communication systems to provide a warning that comes before you are shaken off your feet and your world turns upside down. This scenario is all possible 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, earthquake early warning is here today. 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. Dense geophysical instrumentation in earthquake source regions, with rapid and robust telemetry, and automated processing are required. 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).

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, demonstrating proof-of-concept. Photos show the type of damage that large events can cause in the region. (Image courtesy of R. Allen).

**SIDEBAR #3**

**Ambient Noise and Fault Zone Healing**
Cross-correlating 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 detect 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 velocity after the earthquakes suggests that the fault is damaged by the seismic waves from the earthquake, and the medium recovers (heals) over time. The red line shows a remarkable correspondence with Global Positioning System (GPS) measured displacement along the fault; the filled-in black lower plot is the amount of non-volcanic tremor (low frequency fault energy) occurring over time as measured by local seismometers. The correspondence of the along-fault velocity structure, surface displacement, and non-volcanic tremor suggests stress relaxation in the deeper part of the fault zone. (Image from M. Brenguier et al., Science, 321, 10.1126/science.1160943, 2008)

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

This empirical approach is adequate for moderate earthquakes; however, there are very few on-scale recordings in close to 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 true behavior in the Earth, and encompass the full range of possible behaviors. Further improvements, particularly in validation of simulation results against data, will be required for these simulations to have an important impact on engineering practice. Physics-based ground motion simulation is 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 shear failure during an earthquake as driven by the redistribution of stored strain energy. If the assumptions that go into it are correct, dynamic modeling can serve as the foundation for predicting fault behavior, and hence, for predicting strong ground motion. Dynamic rupture modeling is computationally extremely intensive.
because representations of faults have to span inner and outer spatial scales covering many orders of magnitude, and time-dependent stress must be calculated at all causally connected points to account for stress and slip evolution. Progress has required use of today’s most powerful supercomputers.

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. There is a strong rupture directivity effect and strong amplification 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 rupture model, while the one on the right assumes a dynamic (physics-based) rupture. The difference in the predicted intensities underscores the importance of properly characterizing source processes in such simulations. (Image modified from Olsen et al., BSSA, 98, 1162, 2008)

SIDEBAR #5

Episodic Tremor and Slip (ETS)
The deployment of project Earthscope strain, seismic, and geodetic networks in Cascadia has enabled scientists to unravel the details of how slow slip and tremor evolve. The figure is a 3D view of western Washington and Vancouver Island showing the plate interface between the Juan de Fuca and North American Plates (light grey surface), the Moho of the subducting plate (black surface), locations of tremor during the January, 2007 Episodic Tremor and Slip event color coded by tremor date, region of geodetically inferred slow slip (dark grey shading) and contours indicating where the plate interface is inferred to be 20%, 40% and 60% locked (blue lines). Most of the relative plate motion in the shaded area is accommodated by similar slip events that repeat every 14 months. Slip to the west of the blue lines occurs during great earthquakes such as the M 9 Cascadia Megathrust Earthquake in 1700. The tremor activity clearly migrates, and analyses of strainmeter data are beginning to show a migration of slow slip also, which 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 extends significantly further inland than had been thought, closer to the large population centers of Cascadia. (Image courtesy of K. Creager).
Earthquake Prediction and Predictability

“When will the Big One be?” is the primary question asked of all seismologists by the public. Most people 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 beneath San Francisco on Wednesday”. Answering this question about earthquake prediction has been one aspiration of seismology since the emergence of the discipline.

There are two approaches to finding an answer to this problem. The first is the silver bullet approach - seeking an earthquake precursory signal. The most desirable precursory signal would be something detectible that occurs before all earthquakes. However, no such universal precursory signal has yet been identified. There may be precursory signals that precede only some earthquakes, in specific environments. Candidates that have been explored 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 to answering the earthquake prediction question is to develop our 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. Studying the basic physical processes 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. It is important to note that even if earthquakes could be predicted with a high degree of probability and accuracy, it would not solve 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. If not built to withstand earthquakes, then homes and livelihoods will still be destroyed, so commitment to improving earthquake engineering and mitigation efforts has to be sustained whether or not some level of earthquake predictability is ever achieved.
Grand Challenge 2: 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). However, being a purely kinematic theory, plate tectonics does not quantitatively account for how plates move and deform (strain). Rheology describes the linkage between forcing stresses and strains 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 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. However, causative stresses can thus far only be approximately inferred. Knowledge of these lithospheric stresses is essential to understanding the forces driving deformation at plate boundaries and within plates, and localized redistribution of stress accompanying the earthquake cycle. Seismology plays a fundamental role in the Grand Challenge of quantification of stress and rheology in the lithosphere.
Plate boundary deformations, 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, EPSL, 274, 380, 2008).

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 attributes of stress in the Earth and their relationship to earthquake occurrence, given that stress changes from 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 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 employ the latest in “peta-scale” computing, and can address how stress redistributes as fault systems evolve.

Seismically derived images constrain models 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 stick-slip faulting from creeping behavior of the rock. 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.

Studies of anisotropy, imprinted directionality in the structural and/or mineral fabric that causes seismic shear waves with different shaking directions to travel with different speeds, are providing 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 constitutive laws of faults and surround crust that give rise to slow and fast slip?
- What is the role of pore fluids in the fault zone stress environment?
• What is the relative importance of static versus dynamics stresses for earthquake triggering?
• What is the time-dependent rheology of the crust and mantle?
• How are new faults initiated, and how are old faults reactivated?
• Are observed stochastic characteristics of earthquakes caused by material/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
• Rapid post event drilling into fault zones can quantify frictional heating. Time-dependent hydro-fracture modeling can quantify in situ stresses.
• New offshore deployments of ocean bottom seismometers (OBS), pressure sensors, and seafloor geodetic instruments are needed for understanding submarine earthquake cycles.
• Increase interdisciplinary coordination of stress measurement and calibration procedures.
• Image, in 4D, changes in slip directions quantified relative to absolute stresses.
• Develop of robust anisotropic models for the lithosphere.

SIDEBAR #7

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 direction of fault rupture where the radiation of seismic waves was enhanced. As the waves spread past Bozeman, Montana, 3000 km from the source faulting, they shook local faults, causing them to fail and generating tiny earthquakes. Signals from these local earthquakes (bursts in the lower panel indicated by green arrows) 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 bursts (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. In this case, there is no question that triggering occurred, and these data provide a means by which to determine what stress changes drive frictional instabilities of earthquake faulting. (Image courtesy of E. Brodsky).

SIDEBAR #8

Seismology and Waste Repository Siting
The National Seismic Hazard maps (http://earthquake.usgs.gov/hazmaps/) provide a probabilistic assessment of strong ground motions in any location across the United States that is used as 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, involving shaking from very large events with very small probabilities of occurrence. Historic records only document recent earthquake activity and usually do 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 constraints, respectively. Validation of numerical codes is ongoing using some of the largest computing facilities available today. The search for more constrains on past ground motion is also underway. For example, precariously balanced rocks, precipitous cliffs, and fragile geological formations can be used to bound ground motions experiences over geologic time scales.
Probabilistic seismic hazard curve for Yucca Mountain, Nevada, showing the peak ground acceleration (PGA) against the annual probability of exceedance (P.E.). Most buildings are designed to withstand shaking with a P.E. of around 2% in 50 years or a likelihood of $4 \times 10^{-4}$/yr. The design criterion for the proposed long-term nuclear waste repository at Yucca Mountain is $1 \times 10^{-8}$/yr. 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) was damaged during the July 16, 2007 Mw 6.6 Chuetsu earthquake. The reactor caught fire and there were fluid and gas leaks. The ground motion in this earthquake exceeded the design criteria and the reactor, Japan’s largest, remains closed. (Image courtesy of R. Allen, with graph from J. C. Stepp and I. Wong).
**Grand Challenge 3. How do Processes in the Ocean and Atmosphere Couple to the Solid Earth?**

Seismology readily detects signals from natural sources such as ocean storms and glacier calving. A new era of research has 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 this enables seismic monitoring of ocean processes. 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 over several decades. It has now been established that the primary sources of the “hum” are related to mid-latitude winter storms that generate strong ocean waves that couple to the ocean floor via non-linear mechanisms that are not yet well understood.
Comparison of seasonal variations in the distribution of long period “hum” sources (top) from array analysis using very broad band 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). (Image from J. Rhie and B. Romanowicz, Nature, 432, 55, 2004).

The ocean wave origin of the short-period microseism 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 are now working to elucidate the relationship between Earth’s seismic background excitation across hum and microseism periods to ocean 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). 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.

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 increasing storm duration and intensity. The microseismic and hum noise both track ocean storms. Monitoring changes in wave activity and identifying whether changes have occurred in the wave climate over the past several decades can only be reliably determined from archived near-coastal seismograms.

Seismologists and glaciologists are now collaborating actively in efforts to track how polar ice sheets are falling apart as global warming progresses. Glacial earthquakes largely escaped attention until recently, because they do not generate short period (1–10 s) seismic waves that are used for standard earthquake detection and location algorithms. Glacial sources, such as calving, that involve floating ice systems, 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 ionosphere, where remote sensing using GPS holds potential for new ways to characterize the sources of large earthquakes. An explosion or disturbance near Earth’s surface produces both seismic energy and infrasound energy, the latter being best observed on microbarographs or, at high frequencies, by microphones. Infrasound can be caused by meteors or comets exploding as they impact the atmosphere, or even by changes in atmospheric pressure that causes ground tilt such as the “Morning Glory” observed in Los Angeles. Combining seismic and infrasound recordings can help elucidate the way in which sound waves propagate through the atmosphere, and therefore provides understanding of atmospheric structure and its variation with time at spatial and temporal scales inaccessible by other means.
**Key Questions and Issues.**

- How are Earth’s normal modes excited by phenomena in the atmosphere and ocean?
- How well do seismic background noise variations track climatic changes due to global warming?
- Are models of thermohaline circulation consistent with seismic images of oceanic internal structure?
- Can bounds be placed on the energy budgets associated with bolide impacts, glacial calving, volcanic eruptions, and other sources 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**

- Sustained global observations of very-low-frequency seismic signals on land and on the seafloor are important for evaluating mechanisms of hum excitation.
- Increase the number of co-located infrasound and seismic stations.
- Make hydroacoustic and infrasound data sources openly available for basic research.
- Develop an authoritative catalog of non-earthquake events.
- Install permanent broadband seismic networks in polar regions for long-term observations.
- Large numbers of low-temperature capable broadband seismic and geodetic instruments for portable deployments in polar regions are needed for experiments around ice-shelves, glacial streams, and near glacier outlets.

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**SIDEBAR #9**

**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. Recent research topics also include tectonic evolution of west Antarctica and the history of ice cap changes; studies of tidally modulated ice stream surging in west Antarctica; iceberg seismic and ocean acoustic tremor and breakup processes arising from 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 monitoring and study of a newly recognized class of remotely detectable slow glacial earthquakes from major tidewater outlet glaciers in Greenland. In each application, seismology can quantify 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 Global Seismographic Network associated with major outlet glaciers.
in Greenland, showing seasonality and annual variability. (Image from G. Ekström, M. Nettles and V. Tsai, Science 3211, 1756, 2006).

SIDEBAR #10

Seismic Imaging of Ocean Structure

During routine seismic profiling of sub-seafloor 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 mesoscale 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 sections of it, thus providing the possibility of three-dimensional and time-lapse imaging of the complex oceanic structures involved in oceanic mixing and transport. (Image courtesy of Steve Holbrook).
Grand Challenge 4. How Does the Near-Surface Environment Affect Resources and Natural Hazards?

Earth’s near surface is a critical interface between the solid planet and the hydrosphere, ocean, atmosphere, and biosphere. For seismology, a Grand Challenge is to quantify structures and processes at this interface and to address how seismic waves interact there to produce hazards. These tasks are extremely challenging due to the acute heterogeneity of near-surface Earth structure and associated 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 deep Earth, atmosphere-ocean systems, or human activity. Sediment deposits at or near Earth’s surface are the youngest and therefore record the most recent environmental changes or events (e.g., variability in climate or weather, floods, landslides, earthquakes). Water, energy, and mineral resources at depths of meters to a few kilometers are affected by near-surface processes. Detailed knowledge of Earth’s near surface is therefore a crucial part of managing a sustainable environment for human civilization.

Although well established, near-surface geophysics is verging on explosive growth because of the pressures on our environment. Although the near surface is accessible to drilling and excavation, these activities are complemented in a cost-effective and noninvasive manner by exploration seismology. Seismology provides multiple near-surface imaging methods, including the use of refracted, reflected, and surface waves to produce 3D and 4D (time varying) maps of the subsurface.
A 60-km long cross section of the upper 200 m of the Los Angeles basin, at 100X vertical exaggeration, showing shear-wave speed. Orange regions indicate soils that would most amplify ground shaking during an earthquake. The image was derived using seismic surface-wave background noise. (From W. Thelen et al., BSSA, 96, 1055, 2006)

Shallow seismic methods play a key role in determining a vast range of geotechnical properties. 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 specific soil horizons laterally beneath construction sites. The shear modulus of soils is a critical engineering strength parameter for embankment, buildings, and the foundation of other structures, and it can be quantified in the subsurface by noninvasive seismic shear-wave studies using either controlled sources 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 their hazard and develop 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, non-aqueous phase liquid contaminant. The black lines indicate seismic reflectors and the color scale indicates seismic P-wave velocity. The more prominent black lines and coincident slower (redder) colors outline the contaminated channel. (From Gao et al, Geophysics, 71, H1, 2006)

The strength of earthquake ground shaking is heavily influenced, and commonly amplified, by soils and other shallow geologic structures. Characterizing the seismic properties of shallow deposits is thus crucial to assessing the potential extent of damage from strong ground motions during earthquakes. The potential for soil to liquefy in strong shaking may also be discernable from its seismic properties, such as shear-wave speed and attenuation, coupled with other geotechnical measurements. Ground rupture can be predicted by mapping faults at the surface and in the subsurface using seismically imaged offsets in shallow seismic layers.
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 is 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 flow of natural or human groundwater contamination.

It is usually through a combination of shallow geophysical methods and subsurface sampling that near-surface problems are addressed. Seismic measurements give part of the picture, but the skilled incorporation of gravity, electrical, magnetic, radar, and electromagnetic induction data offers improved characterization of the shallow subsurface. An important challenge is the joint inversion and interpretation of diverse data for a single consistent subsurface model, including the direct identification of sediment, rock, and fluid properties (e.g., porosity and permeability). To date, such joint inversions have required 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?
- 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 changes in permeability at depth?
- Can physics-based predictions of strong ground motion couple with performance based engineering to improve seismic hazard mitigation?
- Can time-dependent properties of shallow aquifers being characterized to monitor water and contaminant transport?
- Can potential ground failures from landslides and karst be robustly characterized?
• Can nuclear testing be monitored with confidence levels necessary for the Comprehensive Test Ban Treaty?
• What is the threshold for detecting unexploded ordinance, tunnels, buried landfills, and other human-made hazards?

Seismological Approaches and Requirements To Make Progress

• Improved 3D wave propagation capabilities for extremely heterogeneous media need to be developed and made broadly available.
• Combined active and passive imaging using ambient noise needs further development.
• 4D characterizations of near-source systems requires dense instrument deployments.
• Cross-disciplinary approaches are needed for material property and nonlinearity quantification.
• Large increases in numbers of inexpensive sensors to enable multi-scale near-surface environments.
• Source facilities for high-resolution shallow subsurface mapping in diverse environments are needed.

SIDEBAR #11

Underground Nuclear Explosion Monitoring and Discrimination

Development of the discipline of seismology has been greatly facilitated by the critical geopolitical need to monitor underground nuclear testing. 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 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 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. The extensive data and research activities have advanced the capabilities of seismic monitoring significantly, particularly the ability to identify signals from small nuclear explosions amidst a background of signals from earthquakes and other natural sources. Whether the CTBT enters into force or not, seismology will continue to play a critical role in monitoring of nuclear testing treaties and activities worldwide.
Identifying seismic sources (discrimination) is a critical problem that has been approached through decades of research and development. As the discipline has advanced, seismology has achieved robust quantitative discrimination of 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. Dreger et al., Science, 321, 10.1126/science.11573292, 2008).

**SIDEBAR #12**

**Seismic Imaging of Proxies for Past Climates**

Determining Earth’s record of natural climate change relies in part on seismic imaging of the shallow sedimentary deposits that record and respond to climatic changes. 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 large enough velocity contrasts to reflect the sound source (but that don’t necessarily directly correlate with sedimentary boundaries), complementing drilling efforts. Seismic stratigraphy at the basin scale and on continental margins has long been used to identify sea level through time. These methods examine, at very high resolution, the shallowest and youngest sediments to constrain climate during the past few hundred thousand years. Drilling programs in lake and ocean sediments are therefore best designed utilizing stratigraphic patterns mapped by 2D or 3D by seismic reflection.
Materials in the pore spaces between mineral grains may contain information about past climates. An important example is gas hydrates (frozen hydrocarbon gases, predominantly methane), which are found at shallow depth below the seafloor along continental margins in water depths of 300–500 m. These hydrates contain a globally significant quantity of carbon. In addition, they hold potential as a vast energy source. Changes in seafloor temperature or water depth can change the stability conditions for frozen hydrates. Such changes have in the geologic past have likely resulted in massive releases of methane gas and CO$_2$ from biologic methane decomposition (both greenhouse gases) into the atmosphere. Because the bottom of the gas-hydrate stability zone acts as a strong “bottom-simulating reflection” for seismic waves (mimicking the shape of the seafloor), Seismology has played a central role in mapping the global occurrence of gas hydrates, including the thickness of the gas hydrate layer, its porosity, and thus volume of hydrates and associated deeper fluid plumbing systems. Deep drilling and remotely operated vehicle sampling of gas hydrates are guided by detailed seismic site studies. Temporal changes in the hydrate layer caused by naturally episodic fluid-flow events such as gas seeps, by climate change, or by human extraction for energy resources can also be monitored using repeated seismic reflection imaging.
Seismic reflection cross-section of the shallow seafloor 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. Inset shows gas hydrate ice. (Image from Trehu et al., EPSL, 2004)
Grand Challenge 5. Where are Water and Hydrocarbons Hidden Beneath the Surface?

The presence of fluids in Earth's interior can be detected by seismic waves because there are large contrasts in elastic 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 rheology and magma production within the deeper Earth. Thus, mapping and monitoring changes in the distribution and circulation of fluids and volatiles in the 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 help attenuate 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.

Water is carried back into the mantle by subduction. Although the amounts at depth, particularly greater than about 400 km, are 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 410-km discontinuity. 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 water is stored as groundwater (the vast majority of near-surface water is either in the planet’s two remaining icecaps or in the ocean). The recharge, flow, and storage of groundwater are heavily influenced by geologic stratigraphy and faults. 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, and reservoir management industry. Seismological techniques, including 4D mapping, can be used to monitor the extraction and movement of hydrocarbons and water in producing fields. Seismic exploration on land and at sea is a multi-billion 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 the carbon sequestration applications.

**Key Questions and Issues**

- How can we improve the detection and characterization of the Earth's 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?

• 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 much water is stored in the transition zone of the upper mantle?

• To what extent does water control slip on faults?

• Does dissolved water contribute significantly to the low viscosity of the asthenosphere?

• Where 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 non-linear effects.

• Expand use of repeated, high-resolution 3D active surveys to yield 4D monitoring.

• Improve techniques for using Earth's noise for continuous monitoring.

• Tomographically image the mantle and crust at higher-resolution.

• Increase collaborations among seismologists, geodynamicists, geochemists, hydrologists, petrologists and electromagnetic geophysicists.

• Expanded the educated workforce, particularly for industry.

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SIDEBAR #13

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 by industry as a cost-effective method of finding, developing, and extracting 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 developed 4D, or time-lapse repeat surveys, to monitor mechanical and fluid changes to the reservoir during resource extraction. Seismology is less commonly used in mineral exploration and development, but has great potential for growth. 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. Exploration seismology is almost absent in the hard-rock mining industry in the United States, but pioneering work in other countries 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.

Caption: 3D perspective of faulted ore-body (yellow) superimposed on a slice through a 3D seismic reflection volume used to find the ore-body in the subsurface. (Image from C. C. Pretorius et al., Geophysics, 65, 1862, 2000)
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 percentage of geoscientists between 31–35 years old is less than half that of geoscientists between 51–55 years old. There are not enough students being produced to fill the positions that will be vacated by retirements. By 2020, the current U.S. workforce + 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 spur employment demand.
IRIS summer intern Justin Brown servicing a seismograph station in Alaska in 2004.

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), low participation by women (30% of the 2005–2006 PhD’s), and low participation rates by 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 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 UNAVCO 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.
Undergraduate IRIS interns in the field in New Mexico.

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SIDEBAR #15

Four-Dimensional imaging of Carbon Sequestration
High-resolution imaging of the subsurface provides models of 3D structures at depth, which include fluids, impermeable rock layers, and subsurface geologic structures. Repeated imaging allows time-dependent changes in the subsurface conditions to be detected, including those from fluid extraction, fluid injection, and reservoir compaction. For activities such as carbon sequestration, where CO$_2$ is injected into deep rock layers to isolate it from the atmosphere, it is important to assess where the CO$_2$ 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 of CO$_2$. A practical example of this is shown above for the CO$_2$ injection at Statoil’s Sleipner field, which has more than 8 Mt of CO$_2$ injected in the reservoir. Time-varying reflection images are computed to determine how the CO$_2$ has distributed in plumes throughout the medium. This method provides a means by which to ensure integrity and full utilization of the sequestration reservoir. (Image from R. A. Chadwick et al., Geol. Soc. London, 6, 1385, 2005)
Grand Challenge 6. How do Magmas Ascend and Erupt?

Volcanic eruptions are some of the most spectacular and often dangerous geological events. Large explosive eruptions can scatter ash over hundreds of kilometers and alter climate for years. Lesser eruptions can introduce ash into the stratosphere that disrupts airline traffic. Lahars or mudflows can race down valleys, wiping out settlements tens of kilometers away from the eruption. Lava flows can gradually or suddenly alter the landscape, covering up man made structures along the way. Poisonous gases that are emitted can be silent killers. Seismology provides probes of volcanic processes both at the surface and in the deep interior, which places it at the forefront of investigating the distribution and dynamics of melting and eruption of magmas. Quantifying the presence and variations of melts inside Earth and understanding how they rise to the surface and intrude or erupt is one of the key Seismological Grand Challenges.

Seismological monitoring is one of the primary ways of forecasting or predicting eruptions. An increase in microearthquake activity and harmonic tremor as moving magma changes the shape of the volcano and fractures the surrounding rock often precedes eruptions by several days, providing some warning. There may be changes in the depth of earthquakes or in their mechanism. Another promising monitoring technique is “4D tomography” – making maps of the 3D distribution of seismic velocities within the volcanic edifice and then monitoring changes in the medium’s velocity with time as cracks open or fluids migrate through the cracks. Seismo-acoustic monitoring of infrasound signals may be able to directly detect and recognize stratospheric ash injection at great distances, providing rapid eruption notification to warn aircraft of hazardous conditions.
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 Alaska Volcano Observatory/USGS).

Current eruption prediction methods are primarily empirically based, because we don’t have enough information to really understand the physics. The deep plumbing system of volcanoes is poorly known. To improve prediction capabilities, we need to better determine the physical changes that accompany eruptions and to better image the interior of volcanic systems.
Ocean bottom seismometer partially buried in new lava flow on the East Pacific Rise. This was part of an experiment monitoring microearthquakes that accompanied hydrothermal activity on the plate boundary and recorded increased seismicity before the eruption. (Image courtesy of the National Deep Submergence Facility, ROV Jason, Woods Hole Oceanographic Institution and the National Science Foundation).

In addition to the hazards posed by volcanoes, volcanological processes are of fundamental interest because they help shape the surface of the planet. Eruptions and intrusions of magma are the primary way that new Earth crust is formed. For example, two-thirds of the Earth is covered by basaltic oceanic crust averaging 7 km in thickness, all formed by magma rising from the mantle at mid-ocean ridge spreading centers at diverging plate boundaries, and all formed in the last 180 million years.

Tomographic image of the ratio between P velocity and S velocity beneath Costa Rica. Red area indicates the presence of magmatic fluids rising from the subducted oceanic plate, indicated by earthquakes extending to depths of 175 km, to the crust beneath the volcanic arc. (Image courtesy of E. Syracuse et al.).
Magma beneath mid-ocean ridge spreading centers is generated by partial melting of hot mantle rocks as they rise toward the surface; the drop in melting temperature as the pressure drops induces melting. In contrast, melt production beneath volcanic arcs in the “ring of fire” surrounding the Pacific is largely created by fluxing the hot mantle with aqueous fluids released from the crust of subducted oceanic plates. In this case, the addition of water lowers the melting temperature of the overlying mantle. Although the composition of the magma, 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 are not known very well. Seismology holds the best promise of imaging the pathways.

Beneath mid-ocean ridges, mantle flow models and low-resolution seismic tomography suggest that melt is produced in a zone more than 100-km across at depths as great as 100-km, yet nearly all of it makes its way to a plate boundary zone less than 1-km wide at the surface. It is not known whether 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. It may also flow through an interconnected network of porous channels.

Volcanic eruptions also occur in intraplate settings away from plate boundaries, ranging from well-known hotspots 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.

**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 melt widely distributed 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 configuration does it ascend? What is the influence of the sinking plate?
• Does melt pond at the base of the crust and thicken the crust by underplating? 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
• Densified long-term broadband seismic, geodetic, and infrasound instrumentation around active volcanoes is needed.
• 4D active source studies and ambient noise studies of volcanoes are needed.
• Experimental constraints on seismic velocity and attenuation properties of rocks with melts are needed.
• Provide open access to data from volcano observatories, with improved data accessibility and metadata.
• Form a “learning from eruptions” program.
• Develop a USGS volcano hazards external grants program with support for seismology of volcano hazards.

SIDEBAR #16

Four-Dimensional Monitoring of Volcanoes Using Ambient Seismic Noise

Seismic noise is a nuisance that obscures transient seismic signals, making it more difficult to detect small earthquakes or to image Earth structure. However, because background noise is continuously generated by physical sources, such as ocean
waves interacting with the shore, it involves seismic waves that propagate coherently across an array of stations. Although the signal’s complexity makes them appear random, by correlating the noise between two stations and averaging it over a period of time, 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 image of temporal variations in the medium can be obtained.

This method of using seismic noise signals provides a tremendous opportunity for inexpensive 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 within a few days, changes in velocity in the volcanic edifice on the order of 0.05% could be recognized and mapped as shown in the figure. 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 in 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.
Map of the cumulative changes in seismic velocity that had occurred just before the September 1999 eruption of Piton de la Fournaise volcano. 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 maximum change in velocity was about 0.1%. Velocity changes before a larger eruption in
July 2006 reached about 0.3% are also shown. Green shaded area indicates period of eruption. (Image from F. Brenguier et al., Nature Geoscience, 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. 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 in the context 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 which is not understood.

Seismic velocity discontinuities beneath the Sierra Nevada, imaged by EarthScope instruments reveal regions of detaching lower crust beneath the mountain range that indicate complexity of continental lithosphere evolution. (Image courtesy of G. Zandt, C. Jones, T. Owens and H. Gilbert).

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, with spurts of growth around 3.3 and 2.7 Ga, which may indicate initial establishment of plate tectonics. By 2.7 Ga, continental cratons seem to have stabilized as regions of
compositionally buoyant and viscous mantle lithosphere isolated from mantle convection due to their relatively low temperatures, distinct composition, grain size, or other properties. Subsequently continents generally increased in size by accretion; seismic studies of lithospheric velocity discontinuities often show that these ancient accretion boundaries remain weak and influence continental dynamics, magmatism, seismicity, hydrothermal, and other key processes on continents today. The deep crust and uppermost mantle also destabilize and delaminate under certain conditions, forming “drips” in which the denser root sinks. Long conjectured, seismic imaging has recently revealed this process to be occurring under the Sierra Nevada and in other locales. Small-scale convective instabilities in the asthenosphere also appear to play an important role within continents, eroding geochemically old mantle, and controlling melt at the lithosphere-asthenosphere boundary. Lateral movement of lithosphere is also important: stacking and thrusting of lithosphere plays an important role in continental evolution and creates features that persist over billions of years. Seismology is critical to investigating and understanding these structures, as surface outcrops are very limited.

Example of seismically imaged continental lithospheric sutures that have persisted into the present. The left-most portion of the figure shows lithospheric fabric from the active source SNORCLE experiment, and the right part of the figure shows these sutures extend under the ~2.7 Ga Slave craton in Canada, based on passive source seismology. (Courtesy of M. Blostock).
Oceanic crust is continually forming at mid-ocean ridges. Heavier minerals in basaltic oceanic crust and cooled upper mantle make the oceanic lithosphere denser than its continental counterpart, beneath which it usually subducts at convergent plate boundaries, hence, the oldest oceanic crust is only about 180 Ma. Oceanic lithosphere thickens as it cools and moves away from the mid-ocean ridge, from zero age to 120 million years old, which is roughly consistent with conductive cooling models; however; the oldest lithosphere is thinner than these models would predict. It is generally hypothesized that small-scale convection plays a major role in this phenomenon, but the exact nature of this convection is still uncertain and the subject of many seismic imaging efforts.

A distinct low seismic velocity zone occurs beneath oceanic lithosphere, associated with the low-viscosity asthenosphere, and this may extend over more than 100-km in depth. The low seismic velocities are caused by some combination of temperatures, melting, hydration, and grain size. Low velocities are often also found beneath continental lithosphere, but the structure is complex. At the asthenosphere-lithosphere interface, distinct seismic velocity jumps have been detected and used to map continental lithospheric thickness variations. It may be that the lithosphere-asthenosphere boundary is not simply a passive feature, but small-scale convection occurs there and is associated with the motion of lithospheric “keels.”
The seismic velocity jump associated with the lithosphere-asthenosphere boundary under New England. As shown by the red text, the S-wave velocity decrease associated with the transition from the lithosphere to the asthenosphere is between 5.3–7.4% and 6.0–9.6%, and occurs over about 5-11 km at a depth between 89–105 km (Image courtesy of C. A. Rychert).

Lithospheric seismology is being revolutionized by new data from large-scale seismometer deployments such as the USArray component of Earthscope, and new techniques such as S-wave receiver functions and “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 cratons form, what is their composition, why did they stabilize, and how
stable are they over time?

- In what ways, and by what mechanisms, do pre-existing structures such as ancient faults or sutures affect modern-day deformation?
- What aspects of melting, grain-scale, and rock-scale processes cause velocity anisotropy, and how can we use this knowledge 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 does small-scale convection and lithospheric delamination occur?
- Where does convection occur in the ocean asthenosphere and does it relate to surface features?
- What is the role of water, other volatiles, and composition in modulating the stability and instability of the lithosphere?
- How is continental crust and lithosphere built? How deep do boundaries associated with accreted terrains extend?

**Seismological Approaches and Requirements To Make Progress**

- Continued deployment of dense portable and permanent seismic arrays on continents and on the ocean floor will provide critical observations of discontinuities, anisotropy, attenuation, and small-scale heterogeneity of the lithosphere and asthenosphere.
- Access to high-performance computing is needed to enable development of new computational methods for demanding full waveform analysis and inversion.
- Inexpensive, abundant seismometers are needed for large-scale active and passive source deployments to image 3D lithospheric structures.
- Close collaboration among geoscientists across a range of disciplines is needed to better understand the roles of fluids, variable rheology, and geologic history of the lithosphere.
Intraplate Earthquakes

Seismologists face a major challenge in estimating earthquake hazards for areas within continental plate interiors, such as the New Madrid and Charleston seismic zones in the central and eastern United States, respectively, for two basic reasons. First, regions far from plate boundaries lack a context for the causes, nature, and recurrence rate of earthquakes. Second, because intraplate earthquakes are rare owing to slow deformation rates, relatively little is known about earthquakes and their effects in these regions.

Geological and paleoseismic observations indicate that seismicity may be episodic on continental intraplate faults, with long quiescent periods, and in some cases the seismicity migrates across fault systems. This may be occurring in New Madrid, Missouri, where GPS geodetic data show little or none of the expected interseismic motion expected before a future large earthquake. Earthquakes in this region in 1811 and 1812 may represent the end of activity, which will migrate elsewhere, or there may be intermittence in the strain accumulation process.

Understanding fundamental earthquake physics is crucial for estimating the earthquake hazard for intraplate areas. Various assumptions yield different results. For example, traditionally it has been assumed that future earthquakes are time independent—equally probable to occur immediately after the past one or much later. An alternative is to use time-dependent models in which the probability is small shortly after the past one, and then increases with time. Applying such models to New Madrid and Charleston predicts significantly lower hazards because these areas are “early” in their cycles. However, if the New Madrid cluster is ending, the earthquake hazard in the New Madrid zone would be much lower than either model predicts.
Comparison of hazard maps for the South Carolina area based on time-dependent model assumptions. Colors show peak ground acceleration (PGA) with 2% probability of exceedance in 50 years as percentages of 1 g. Compared to the hazard predicted by the time-independent model, the time-dependent model predicts lower hazard for the periods 2000–2050, 2100–2150, and 2200–2250. (Image courtesy of S. Stein).

Processes occurring at plate boundaries result in some of Earth’s largest natural hazards—great earthquakes and active volcanoes. Plate boundary processes also strongly influence Earth’s surface over broad regions, including mountain ranges, continentalization, back-arc rifting, and crustal extrusion. A Grand Challenge in which seismology plays a major role is understanding the evolution of the multi-scale processes that occur in the distributed zone around plate boundaries, which are linked to the natural hazards and geology of these regions.

Comparison of the idealized rigid plate boundaries (thin lines) and the broad regions currently undergoing diffuse deformation (red) as indicated by seismicity, topography, and other evidence of faulting. Source: [http://www.unavco.org/](http://www.unavco.org/)

Multidisciplinary geophysical networks 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, across plate boundaries, providing records of deformation that constrain plate rheology. The density of observations is beginning to allow assessment of the role geology plays in driving the development of boundary faults, 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 are providing data that are transforming our understanding of the plate boundary. For example, focused research in the Pacific Northwest is beginning to unveil the history of subduction of the Juan de Fuca Plate and its connection to tectonic processes throughout the western United States, including the Yellowstone hotspot. The San Andreas Fault system is one of the most-studied plate boundaries at the surface, with extensive seismological and geodetic data collection efforts. Through EarthScope, seismologists are now mapping the deeper structure in great detail, revealing how the pattern of crustal deformation is related to the structure, composition, and physical properties of the lithosphere and mantle beneath.

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, or plumes, generating volcanism at the surface. 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 the upwelling plume, which appears to have torn the slab from north to south. (Image courtesy of R. Allen).

Oceanic plate boundaries are just as complex and diffuse as continental plate boundaries, but we have relatively little information on their structures and processes. The melting processes at mid-ocean ridges are passive processes responding to distant plate forces, and while the newly generated crust is an extremely uniform 7 km thick, melting of the mantle occurs to 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 residual mantle beneath. The melt pathways generated by this process remain enigmatic, largely due to the limited data and instrumentation available for study of seafloor processes.

Interpreted cross-section from the 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, Science, 280, 1215, 1998).
In plate boundaries regions with dense geophysical instrumentation, seismologists are now quantifying the distribution of deformation and imaging the primary structural units. By understanding the forces acting at plate boundaries, and their structure and rheology, we can begin to build dynamic models of these systems.

**Key Questions and Issues**

- Is the surface deformation driven by crustal properties or by forces transmitted to the surface through the lithosphere?
- Are mantle wedges strongly coupled or decoupled from subducting slabs?
- How does continentalization occur in back-arc basins?
- How do sinking slabs interact with mantle upwellings?
- What causes deep earthquakes and what are the stress and thermal conditions in deep slabs?
- How and why do ridge jumps occur?
- How much lateral transport of melt is there along ridge segments and between ridges and hot spots?
- How are continental deformations in broad plate boundary zones accommodated at depth?
- How do accretionary prisms evolve and what is their influence on trench migration?

**Seismological Approaches and Requirements To Make Progress**

- Deploy integrated geophysical observatories with long-term operation in multiple plate boundary environments.
- Deploy active and passive source seismic sensors in large numbers in back-arc basins, coordinated with geodetic, geologic and geochemical investigations.
- Deploy a large number of OBSs in diverse mid-ocean ridge spreading environments.
- Acquire 4D multi-channel active source seismic images and drill at active margins.
- Conduct large-scale passive imaging experiments along subduction zones.
Dense instrumentation facilities and deep drilling into active fault zones are an essential approach to understanding complex plate boundary systems. The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) experiment is drilling into 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, and 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 key field laboratory efforts.
SIDEBAR #19

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 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, but specially designed instrument deployments are needed for improving our constraints on deep earthquake processes.

Edge-on view of deep Tonga seismicity, 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 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 the 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 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 dynamics.

3D configuration 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. (Image courtesy of G. Masters).

The very large-scale 3D elastic wave velocity structure of the deep mantle is now fairly well known and is characterized by two huge 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-day 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 episodic 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 constitutes strong evidence for distinct composition of these large masses in the deep mantle, and deep mantle dynamics must involve thermo-chemical convection.

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 chemistry and temperature variations in Earth’s interior, and associated density heterogeneity. This information then informs geodynamical simulations that seek to reconcile mantle flow models with the seismic observations. There remains evidence for some level of chemical stratification between the upper and lower mantle in order to match observed seismic measurements, but new discoveries from mineral physics such as the probably 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 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 hot spot volcanism. This lack of resolution results from a combination limitations in global sampling by seismic waves due to lack of seismic stations in the ocean and in the southern hemisphere, in particular, and limitations of seismic imaging theory and applications that are currently being used. Improved 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 structure of the fluid outer core and solid inner core to high precision. 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 structure both in the outermost 100 km of the outer core and 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. The inner core is solid, but has been found to be surprisingly heterogeneous on many scales. It exhibits radially varying anisotropic structure, hemispherical heterogeneity, and heterogeneous attenuation properties. 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 mantle convection system?
• How much flux of material, and on what time scales, is there between the upper and lower mantle?
• What are the relative contributions of thermal, chemical, and mineralogical variations to seismically detected heterogeneity?
• Are there thermal plumes in the mantle?
• What is the longevity of chemical heterogeneities in the deep mantle and the effect on the overall convective pattern?
• What is the nature and cause of deep mantle anisotropy?
• When did the inner core form and what are its influences on the geodynamo?
• How is heterogeneity of the inner core related to its growth processes and what are the consequences of this heterogeneity?

Seismological Approaches and Requirements To Make Progress
• Expanded global coverage with permanent broadband seismic stations, including into the ocean basins, is needed to improve resolution of global structure.
• Large portable deployments of three-component broadband sensors are needed to resolve deep anisotropy and assess the fine-scale components of heterogeneity in the deep mantle.
• Large data sets need to be applied in imaging methods that use finite-frequency theory and wavefield backprojection to resolve deep structure.
• Interdisciplinary communication among seismologists, mineral physicists, and geodynamicists is needed in workshops and community organizations such as the CIDER program.

SIDEBAR # 20

The Mysterious Inner Core

Seismology reveals that Earth’s inner core is surprisingly complex. While small, the inner core plays an important role: freezing of the solid inner core 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 in depth and
laterally, including multi-scale variations in attenuation and anisotropy. To first
order, the inner core has an overall anisotropic structure, such that waves travel
faster from pole to pole than they do across the equator. 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 less attenuation, 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 compressional waves
transmitted through the inner core over decades (a strong argument for long-term
operation of high-quality seismic observatories). The travel time change is very
small, involving tenths of a second difference on the same path traversed decades
apart. The source of the torques driving either a differential rotation or wobble of
the solid inner core may be electromagnetic in origin and related to time variations
in fluid flow or gravitational in origin and related to heterogeneities at the base of
the mantle. An alternative to the hypothesis of differential rotation may be
episodes of rapid growth or decay of topography of the inner core boundary.
Confirming either of these hypotheses or a new hypothesis will shed light on the
mechanism of growth of the inner core, which adds millimeters per year to its
radius. This process of growth is critical to the thermal evolution of the core and
the cooling history of the planet.
Top: Outer core flow predicted from heat transport out of the core-mantle boundary inferred from lower mantle tomography. Bottom: Predicted regions of outer core upwelling (red) and downwelling (blue) near the core mantle boundary. Contours of the region of fast compressional wave velocity observed in the uppermost inner core in its quasi-eastern hemisphere (Image from J. Aubert et al., Nature, 454, 758, 2008).

SIDEBAR #21

**Planetary Seismology**

Seismology can potentially reveal internal structure and dynamic processes of other terrestrial 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 important 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, and possible existence of a partially molten silicate core. Deployments of seismometers on other planetary bodies can potentially address many significant scientific problems, such as the extent of water within the crust 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 important 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 faulting quakes, 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 bimodal surface morphology of the planet.

Venus and Mercury present formidable environmental challenges, but seismological technologies that can overcome them may be within reach. Smaller planetary bodies like Europa and Ganymede are good targets for using seismological methods to determine the presence and extent of internal fluid water levels. Asteroids have highly uncertain material properties, and design of seismological probes of their interiors can complement other approaches such as ground-penetrating radar. Essentially every mission to a solid body in the solar system should include consideration of the potential of seismological instrumentation and data collection given the great payoff from even limited seismic recordings.
Grand Challenge 10. *How Are Earth’s Internal Boundaries Affected by Dynamics?*

Internal boundaries in the Earth result from primary compositional layering (the crust, mantle, and core) and from phase changes (transition zone and deep mantle velocity discontinuities and the inner core boundary) that can have accompanying changes in composition and rheology. These boundaries can 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, as travel-time tomography is better for resolving volumetric heterogeneities. Detailed imaging of, and extracting information about the thermal, compositional, and dynamical processes near Earth’s internal boundaries, are the principal components of one of the Grand Challenges for Seismology.

![Surface topography and bathymetry around South America](image)

Surface topography and bathymetry around South America (top) overlays variable topography on Earth's upper mantle phase transition
discontinuities at 410 km (middle) and 660 km (bottom) depth (topography is contoured in 2 km increments). 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 oceanic lithosphere descends into the mantle. (Image courtesy of N. Schmerr).

Radial models of the mantle include globally extensive seismic velocity jumps at depths of 410 km, 520 km, and 660 km, which are generally attributed to phase changes in major upper mantle minerals such as olivine. Laboratory and theoretical calibration of the pressure-temperature-composition behavior of mantle minerals allow the seismic observations to be interpreted in terms of absolute temperatures and compositional models. High-resolution imaging of lateral variations in depth of the discontinuities then provides 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 affect mantle circulation profoundly. Many other seismic reflectors have been detected in the upper mantle over localized regions, notably under cratons and in back-arc basins, and the widespread lithosphere/asthenosphere boundary.
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 and are not readily accounted for by standard upper mantle petrological models. (Image courtesy of Y. Zheng).

Boundaries in the deep mantle have also been detected, both in 3D scattering images of near-vertical mid-mantle heterogeneities that are plausibly deep slab effects, and in imaging of sharp edges of the large low-velocity provinces under the Pacific and Africa. There is also a widespread reflector of seismic waves found from 200–300 km above the core-mantle boundary. This boundary is now widely attributed to the recently discovered mineralogical phase transition from magnesium-silicate perovskite to post-perovskite. Seismic waves also reveal the presence of an extensive, but intermittent very thin (< 30 km) ultra-low velocity zone located right 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.
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 et al., Science, 315, 1813, 2007).

Analysis of boundary layer processes provides internal temperature probes along with constraints on rheology and composition. Improved constraints from seismology play a unique role in understanding these boundaries, the existence of which would be unknown without seismic observations.

**Key Questions and Issues.**
- How sharp are internal mantle and core boundaries?
- What is the small-scale 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 from upper to lower mantle?
- Are there sources of thermal 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?
• To what extent can seismological observations constrain heat flux across the boundaries?
• 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

• Dense seismic array observations are needed for resolving fine-scale structure of boundaries in the upper and lower mantle and core.
• Seismic wave propagation methods for handling rough boundaries and for imaging their 3D configurations need to be enhanced.
• Expanded global coverage of boundary structures is needed with new sites in the oceans and at high latitudes to better constrain the structure of Earth’s mantle.
• Communications with mineral physicists and geodynamicists need to be fostered to formulate testable hypotheses that Seismology can pursue

SIDEBAR #22

Core-Mantle Boundary Heat Flow.

About 25 years ago, seismologists reported the presence of 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 geotherm 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 indicate that this model may be what is occurring, with paired velocity increases and decreases at different depths. These velocity changes provide two estimates of temperature at closely spaced depths, enabling an estimate of the temperature gradient. 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, and inner core growth.

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 could 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. Such paired discontinuities have been observed and used to estimate thermal gradients and heat flow based on the temperature calibration from mineral physics. (Image from J. W. Hernlund et al., Nature, 434, 882, 2005).
Sustaining a Healthy Future for Seismology

The remarkable panoply of seismological research topics and societal applications reviewed in this plan is the result of extensive investment by a number of federal agencies, industry, and universities. Sustaining the positive trajectory of seismology’s 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.

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 that prepare new seismologists for tomorrow’s challenges. Retention of this talent and expertise in industry, national laboratory, academic, regulatory, and federal agency careers requires sustained collaboration between 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 undergraduate and graduate students to the discipline.

Building and Sustaining the Professional Pipeline. 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:

- Seismology community organizations should engage with industry to increase awareness of opportunities in seismology amongst undergraduate students.
E&O efforts of these organizations should expand efforts to promulgate public awareness of the discipline and its societal contributions, along with supporting undergraduate and graduate training materials and educational opportunities.

Enhancing Access to High-Performance Computing Capabilities. Increasingly large seismic data sets, inversion for 3D and 4D multi-scale models of Earth’s interior, and robust calculation of broadband seismic ground motions for realistic, non-linear earthquake and explosion sources present enormous computational challenges that exceed the capabilities of the most advanced computers presently available. Advancing university research on these topics will rely on access to resources ranging from moderate-size in-house computer workstations and clusters and the large-scale computational capabilities, such as those at national laboratories in tandem with integrated cyberinfrastructure networks such as Terragrid. 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 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:

- Carefully vetted seismological software and processing tools, along with integrative data products, should be made openly available to the research community.
- Ensure data storage and on-line open access in perpetuity.
- Readily accessible pathways to facilitate the use of massive computer resources should be established through academic, industry, federal (e.g., national laboratory) and other collaborations.

Sustaining Global Observatories. The open availability of high-quality, widely distributed recordings of ground motion lie 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 (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 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

• Coordination with other environmental monitoring facilities and communities should be advanced to establish multidisciplinary monitoring stations at global seismic facilities, as well as to augment global seismic instrumentation.

• Sustained support of IRIS/USGS GSN long-term operations should be shared by all federal agencies that rely upon global seismic data as part of their operations.

• Completion of the ANSS by the USGS is a priority.

• Continued support for the operations of the ISC, which assembles catalogs from many international networks will benefit all users of seismological bulletins.

Advancing Portable Instrumentation. Large pools of portable instruments are essential for seismological investigations of continental and oceanic environments at higher resolution, which is afforded by permanent stations. These resources also allow for flexibility in studying targeted regions of special interest and activity (e.g., active volcanoes, aftershock zones, natural laboratories for key lithosphere-scale processes on land and in the ocean). The IRIS Program for Array Seismic Studies of the Continental
Lithosphere (PASSCAL), EarthScope Transportable Array and Flexible Array instruments, Ocean Bottom Seismometer Instrumentation Pool (OBSIP), and Marcus G. Langseth research vessel all 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 motivation. 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 sub-surface 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

• Federal agencies need to sustain seismic data collection and open data distribution facilities with long-term amortization and investments in new technologies.
• Increasing the pool of three-component broadband sensors is required for next-generation imaging efforts of crustal and lithospheric structure with improved resolution and 2D deployments.
• The EarthScope Transportable Array deployment should be supported through completion of its traverse across the United States, including Alaska.
• Global ocean bottom borehole installations should be deployed, guided by the Ocean Seismographic Network plans for establishing uniform global coverage of the Earth should be carried out.
• Expansion of portable OBSs for systematic large-scale deployments in portable arrays is highly recommended.
• Significant increases in sensors for active source experiments, including three-component systems, are essential for advances to occur in high-resolution crustal imaging.

**Controlled Seismic Source Support.** The highest-resolution imaging of the near-surface through the crust requires densely distributed controlled seismic sources recorded by dense receiver arrays. The NSF-funded research vessel *Marcus G. Langseth* has a large airgun array and four 6-km streamers of dense hydrophones, which 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 seismologic research on very shallow structure, which may require increased flexibility in the current operation of this facility. However, NEES vibrators lack sufficient capabilities for crustal-scale imaging. The controlled-source seismic imaging efforts of the USGS have substantially diminished 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. A community source facility that includes drill rigs,
explosive-handling capability, and a vibrator array 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 expertise for the contract hiring of industry rigs where appropriate and cost effective.

RECOMMENDATIONS

• Sustained and improved availability of seismic sources such as the vibrator trucks of the Network for Earthquake Engineering Simulation (NEES) is needed for near-surface imaging applications.

• Reinvigorated participation of the USGS in active-source seismology is recommended. The explosive-handling capability of the USGS is very beneficial to active source research.

• A facility or collection of facilities for sources used in active-source seismology is needed if research programs and education in this area are to be sustained. It could possibly be developed in partnership with industry.

• Improved interactions between academic, governmental and industrial efforts in active-source seismology are needed to sustain the discipline.

• Expand the ability to conduct 3D active source imaging at sea.

Enhancing Free and Open Access to Data. Seismology is an intrinsically global and international undertaking, and it relies on 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 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 the discipline in the developed world can be leveraged to enfranchise and bolster progress in developing nations struggling to deal with challenging hazard issues and limited resources.

**RECOMMENDATIONS**

- *Federal programs and seismology organizations need to continue to strongly advocate for real-time open-access to seismic data on a global basis.*
- *Integration of regional and global seismic bulletins into an openly-available definitive international seismic source catalog should be undertaken.*
- *Seismological capabilities for addressing hazards and environmental monitoring concerns and data exchange should be communicated and fostered with developing nations by international coordinated 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 the 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 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 much narrower 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 between science communities, funding agencies, and industry.

RECOMMENDATIONS

• Multidisciplinary integration efforts need to be sustained, and improved communications and coordination on Seismology activities needs to be fostered among NSF Earth Sciences (EAR), Ocean Sciences (OCE), Atmospheric Sciences (ATM) and the Office of Polar Programs (OPP) divisions. Coordination at the Geoscience Directorate level of NSF can help to overcome existing institutional barriers to effective cross-divisional Seismology activities.

• Interdisciplinary workshops on critical interfaces in the shallow Earth system, extreme environments, and environmental change with active participation by seismologists should be encouraged and supported by federal and state agencies, universities, and scientific organizations.

Advances in Instrumentation. Technological advances permeate the discipline of seismology, which has been a scientific leader in embracing advances in computer storage and 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 of 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 the 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

- Collaborations across federal agencies that utilize very broadband seismic data for monitoring purposes should support development of next-generation very broadband seismometers to replace current instruments.
- MEMS technologies need to be explored to develop low-cost seismic sensors that can be deployed in great numbers and can supplement or replace current seismometers.
- Partnerships among industry, national laboratories, academia, and federal agencies must be developed to advance and sustain seismic instrumentation innovation and capabilities.
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 defined 10 Grand Challenge basic research questions where seismology offers fundamental contributions. These topics all address Earth systems that can be probed and quantified by using seismological techniques. This document identifies scientific challenges and opportunities for basic research in seismology to be supported by federal and Industry programs. It is hoped that this document will usefully inform and inspire 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 seismic 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 investigation of 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 of earthquakes 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 exotic 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, where dense networks of seismometers are involved in every case.
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).

All seismic monitoring applications can be enhanced by increased number of stations. Japan has led the world by deploying the densest networks of 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 very high priority.

**Multi-Scale 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 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. 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 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 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 aspherical P-wave and S-wave heterogeneity of the crust, mantle, and core have been determined. Global images are nonuniform in resolution due to the distributions of sources and receivers, and significant improvements in models are driven primarily by new data-collection efforts in previously unsampled areas or with finer station spacing than before. Imaging of oceanic crust and upper mantle structured 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's 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.

The state-of-the-art in exploration seismology involves both 3D and 4D imaging, involving acquisition, processing, and interpretation of huge seismic data sets. The targets of 3D imaging are now very complex subsurface structures, which 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 multi-scale 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 of 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 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 will enable of 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 hardware.
Recommended Additional Reading


List of Acronyms and Titles

AGU – American Geophysical Union
ANSS – Advanced National Seismic System
ATM – Atmospheric Sciences Division of the NSF
CIG – Computational Infrastructure for Geodynamics funded by the NSF
CIDER – Cooperative Institute for Deep Earth Research
CISN – California Integrated Seismic Network
COMPRES – Consortium for Materials Properties Research in Earth Sciences
CSED – Cooperative Studies of the Earth’s Deep Interior
CTBTO – Comprehensive (Nuclear) Test Ban Treaty Organization
DMS – IRIS Data Management System
DoD – Department of Defense
DOE – Department of Energy
EAR – Earth Sciences Division of the National Science Foundation
EarthScope – NSF/USGS/NASA Major equipment facility for studying North America
EERI – Earthquake Engineering Research Institute
FDSN – International Federation of Digital Seismograph Networks
FEMA – Federal Emergency Management Agency
GEO – Geosciences Directorate of the NSF
GEOSS – Global Earth Observation System of Systems
GPS – Global Positioning System
GEOSS – Global Seismic 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 Project
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 of the National Science Foundation
NASA – National Aeronautics and Space Administration
NEES – Network for Earthquake Engineering Simulation funded by the NSF
NEIC – National Earthquake Information Center operated by the USGS
NEON – National Ecological Observatory Network funded by the NSF
NOAA – National Oceanic and Atmospheric Administration
NSF – National Science Foundation
OBS – Ocean Bottom Seismometer
OBSIP – Ocean Bottom Seismometer Instrumentation Pool funded by the NSF
OCE – Ocean Sciences Division of the National Science Foundation
OOI – Ocean Observatories Initiative funded by the NSF
OPP – Office of Polar Programs of the NSF
PASSCAL – IRIS Program for Array Seismic Studies of the Continental Lithosphere
PGA – Peak Ground Acceleration
RESESS – Research Experience for Solid Earth Science for Students
RIDGE – Ocean ridge research program of the NSF
SAFOD – San Andreas Fault Observatory at Depth
SAGE – Summer of Applied Geophysical Experience
SCEC – Southern California Earthquake Center
SEG – Society of Exploration Geophysicists
SSA – Seismological Society of America
UNAVCO – University consortium for measurement of crustal deformation
USGS – United States Geological Survey