Seismological Grand Challenges in Understanding Earth’s Dynamic Systems
This report is drawn from the many presentations and discussion at the September 18-19, 2008 workshop on a Long Range Science Plan for Seismology, held in Denver and attended by ~120 members of the seismological and geophysical research community. Financial support for the LRSPS Workshop was provided by the National Science Foundation. Logistical support for the LRSPS Workshop and for preparation and dissemination of this report were provided by the Incorporated Research Institutions for Seismology (IRIS). Initial drafts of this report were openly available and commented on by the seismological community. This final report is being submitted to the National Science Foundation and other Federal agencies.
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Executive Summary

Seismology, the study of Earth’s elastic vibrations, the sources that generate them, and the structure in which they propagate, is a geophysical discipline with a remarkable diversity of applications to societally-critical issues and a leading role in addressing many of the key scientific frontiers involving Earth’s dynamic systems. Seismology enjoys quantitative foundations rooted in continuum mechanics, elasticity, and applied mathematics, and utilizes state-of-the-art digital ground motion recording and communications systems. Using a diversity of sensors, seismologists ‘keep their ear’ on Earth’s internal systems, listening for signals from natural and human-made energy sources distributed around the globe and using those signals to quantify the wave sources and to determine structures and processes at all depths in the planetary interior at higher resolution than possible by any other approach. Breakthroughs in theory and data processing now allow every byte of seismological data acquired to be used for imaging sources and structures in the dynamic system, extracting coherent signal from what had previously been dismissed as background noise. Recordings of ground motions are intrinsically multi-use; seismic data collected to monitor any particular Earth phenomenon, such as underground nuclear tests, can be directly used in unrelated studies of earthquake sources or deep Earth structure. This places great value in the prevailing philosophies of open data access and real-time data collection that the U.S. seismological research community has embraced.

Analysis of seismic vibrations plays prominent roles in energy and resource exploration, earthquake detection and quantification, volcanic-eruption and tsunami-warning systems, nuclear testing treaty monitoring, aquifer characterization, earthquake hazard assessment and strong ground motion prediction for the built infrastructure, including lifelines and critical facilities. Seismology provides key information about glacier sliding and calving, landslide mass movements, containment of underground wastes and carbon sequestration and other topics relevant to climate and environmental change.

The rich panoply of societal applications of Seismology has emerged directly from basic seismological research programs focused on understanding Earth’s internal wave sources
and structure. 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 Research Grand Challenge topics:

- The physics of fault failure
- Stress and rheology of the crust and mantle
- Physical coupling of the atmosphere/ocean/solid Earth systems
- Critical interfaces and seismic waves in the near-surface environment
- Distribution and circulation of fluids and volatiles in the Earth’s interior
- Magma dynamics in the Earth’s interior
- Evolution and coupling of the Lithosphere and Asthenosphere
- Dynamical systems at plate boundaries
- Thermo-chemical structures and dynamics of the mantle and core
- Earth’s internal boundary layer processes

Further seismological research on these topics will both address fundamental problems in understanding how Earth systems work, along with augmenting applications to societal concerns about natural hazards, energy resources, environmental change, and national security. Highlights of the seismological contributions, research frontiers and required infrastructure for progress on the 10 Seismological Grand Challenge topics are described in this report. The essence of seismological practices and approaches are further defined by discussion of two key disciplinary practices: (1) Monitoring dynamical processes in Earth’s environment and (2) Multi-scale 3D and 4D imaging of Earth’s complex systems and synthesizing seismic waves in the resulting models. Selected examples of recent research advances across the discipline are used to highlight the rapid progress, outstanding challenges, and diverse applications of Seismology for studying Earth’s dynamic systems.

Sustaining a healthy national research capability in Seismology to pursue the many societally-important applications of the discipline and to address the ten Seismological
Grand Challenge topics requires sustained and expanded support of seismic data acquisition, archival, and distribution facilities. Global seismological observatories with a commitment to long-term operation, and pools of portable instruments for land- and sea-based deployments provide the key observations essential to tackling the Grand Challenges. Oceanic vessels for multi-channel seismic data acquisition are essential for the research community, as is expanding the sparse instrumental coverage of the vast areas of unexplored ocean floor. Governmental facilities to support explosion sources for high resolution crustal imaging are needed to support the Grand Challenge efforts. Completion of the planned deployment of the EarthScope Transportable Array across the conterminous U.S. and Alaska is important for achieving goals of that major NSF program. International participation in open seismic data exchange for diverse seismic networks around the world must be increased. 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 academic support for attracting quantitatively-oriented, diverse graduate students to the discipline is required. This should be abetted by building on current education and outreach efforts of the seismological community, and by developing stronger partnerships between academic, industrial and government laboratories impacted by the Seismology workforce issue.

Seismology holds great promise for achieving major new breakthroughs on the Seismological Grand Challenge topics and associated societal applications over the next few decades, as long as Federal agencies and industry 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 solving 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 the way the planet 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 detection. 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 the surface is disrupted. These ground motions all involve seismic waves, originating in the rocky interior of the Earth by various processes that suddenly release stress, such as rapid sliding motions across a fault, resulting in propagating disturbances that expand outward from the energy source through the rocky interior as seismic P-waves and S-waves. About 140 years ago, scientists first developed instruments to record these vibrations of the ground as a function of time, and theoreticians drew upon solid mechanics and elasticity to develop understanding of these seismic waves that shake the ground. Thus commenced the discipline of Seismology, which involves the study of seismic waves, their sources, and the medium in which they propagate. Because it is fundamentally a remote-sensing discipline, the field has driven mathematical methods for inversion and inference, leading to quantitative models for structures and sources that guide many Earth Science research and monitoring efforts. The discipline, while still young, has grown remarkably into a major international endeavor, developing a tremendous 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 transmit.

Placing ground motion sensors, or seismographs, on the Earth is akin to putting stethoscopes on the Earth system, listening for the internal rumblings and gurglings of the planet’s internal processes. Over the past century seismologists have learned how to unravel the vibrating messages, applying quantitative elastic wave theory to accumulating data bases and distilling meaningful information from the cacophony of seismic motions. Classic applications involved the location and quantification of earthquakes associated with sudden shifts of rock due to frictional instabilities on faults, and construction of models for Earth’s elastic wave properties as functions of depth from the surface to the center of the Earth. This dual effort to study earthquake sources and Earth structure is
now mature and still frames the discipline; great progress has been made as seismic recordings accumulated from stations around the world have been analyzed.

Human-created energy releases, such as buried explosions and large vibrating trucks, provide controlled seismic wave sources at Earth’s surface, used to illuminate the shallow crust with elastic waves, enabling very high resolution of subsurface conditions and detection of energy and mineral resources. Seismology intrinsically provides the highest resolution of physical properties in the inaccessible interior from the crust to the core, with the shallow structure revealing essential energy resources that power society. When nuclear testing moved underground during the Cold War, it became clear that Seismology provides a robust means for remotely monitoring weapons development programs of foreign nations. With these new roles in petroleum exploration and national security complementing earthquake monitoring applications and earth structure research, Seismology rapidly grew into a major high-tech research discipline. Now global networks of sensors transmit ground motion recordings from around the world in real time via satellite, microwave or internet telemetry to data analysis centers. Massive deployments of land- and sea-based instruments record both active human-made sources and passive natural sources of seismic waves, revealing multi-scale structures of the crust and deep Earth. Huge data repositories freely provide the data to all researchers, enabling research and applications across academic, government, and commercial sectors. The size and complexity of seismic wave processing and modeling efforts applied to the accumulated data has placed Seismology as one of the primary drivers of high performance computing at universities, national laboratories and industry for many decades.

A defining attribute of seismic records is that their fundamental nature is simply ground motion as function of time, thus seismic data recorded by a network of sensors for any one purpose, such as monitoring nuclear testing or earthquake hazard analysis, intrinsically provide signals valuable for multiple unrelated uses. One can equally-well study Earth structure, earthquakes, explosions, volcanic eruptions and other processes with the same data. Studying the diverse Earth systems requires sensors around the world and international collaboration and coordination on data acquisition and data exchange.
The multi-use attribute of seismic signals places great premium on continuously recording ground motions, archiving all recordings, and openly sharing the data within and between nations, no matter what the original motivation was for deploying the seismic instrumentation. The U.S. seismological community, along with international partners in the Federation of Digital Seismic Networks (FDSN), have strongly fostered the notion of open-access of seismic data, establishing data centers accessible to all researchers. Because the data play critical roles in rapid evaluation of short-term changes in the Earth’s dynamic systems (earthquakes, volcanic eruptions, explosions, mine collapses, landslides, etc.), near real-time access to seismic data is also of great importance, and whenever it is possible to transmit the ground motion data to open archives in real-time, multiple societal applications of the signals are enabled.

Because seismic recordings of ground motion are not exclusive to any one type of vibration, many dynamical processes can be heard by keeping our ‘ear to the ground’, 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, and oceanic circulation. By its very nature, Seismology is intrinsically sensitive to active, dynamic processes happening today in the Earth’s dynamic systems, even while Seismology can reveal information about ancient processes as recorded in rock structural properties at depth. With modern Earth science research addressing complex physical systems that involve interfaces between 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, 2008; IUGG, 2007), and an alphabet soup of research community organizations (CIDER, COMPRES, CSEDI, FDSN, IASPEI, 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 hydrology, glaciology, and atmospheric sciences.
This centrality of Seismology 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.

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

- Creation of the open-access seismic data repository of the Incorporated Research Institutions for Seismology (IRIS) Data Management System (DMS). This facility, housing terabytes of data freely delivers seismic data to the entire world, an approach being emulated internationally. Providing all researchers with access to data enables proliferating discoveries and societal applications. (FIG. 1. NEAR HERE)

- The discovery of coherent information contained in recorded seismic ‘noise’. The background vibrations of the Earth contain information about sources and structures that was not recognized until recently. Processing of multiple station data allows every data byte to be used for scientific application, and entirely new approaches to structural studies and investigations of changes in the environment have ensured. (FIG. 2. NEAR HERE)
FIG. 1. The cumulative terabytes of seismic data archived at the IRIS Data Management Center (top) for the major seismic network types whose data are managed by the IRIS DMC. There are other smaller data types as well that are not shown. The total volume archived at the IRIS DMC as of the end of August 2008 was 81.3 terabytes. The annual number of terabytes shipped from the IRIS DMC by the same seismic network types. These numbers are not cumulative. The DMC ships approximately twice as much data to the research community each year compared to new data arriving at the DMC, and anticipates shipping more than 35 terabytes to end users in 2008.

FIG. 2. Rayleigh wave group velocity map, 8 sec period. By cross-correlating up to three years of continuous data from 512 stations in the western USA, inter-station empirical Green's functions for all available station pairs are recovered. The USArray Transportable Array and various regional networks provide data for this work. The map derives from an inversion of more than 60,000 group velocity measurements. Thick black
lines define the major tectonic boundaries in the region. (This figure has been updated and modified from one published in: Moschetti, M.P., Ritzwoller, M.H., Shapiro, N.M., Surface wave tomography of the western United States from ambient seismic noise: Rayleigh wave group velocity maps, Geochem. Geophys. Geosyst., 8, Q08010, doi:10.1029/2007GC001655.)

FIG. 3. The 2001Kokoxili Mw 7.8 earthquake ruptured about 400 km along the Kunlun fault in 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 of the time dependence of this radiation shows that the rupture propagated at ~2.6 km/s for the first 120 km and then accelerated to ~5.7 km/s, a supershear velocity which continued for at least 290 km from the epicenter (Walker and Shearer, 2008). Reference: Walker, K. T., P. M. Shearer, Illuminating the near-sonic rupture velocities of the intracontinental Kokoxili Mw 7.8 and Denali Mw 7.9 strike-slip earthquakes with global P-wave back projection imaging, J. Geophys. Res., in press, 2008.
• Recent discovery of a continuous spectrum of faulting behavior, ranging from conventional earthquakes, some of which rupture at great speeds (super-shear velocity ruptures) and some of which involve anomalously slow ruptures, even some so slow that fault sliding does not radiate seismic waves. This has unified seismic and geodetic monitoring of fault zones and provides brand new insights into frictional sliding and earthquake hazard. (FIG. 3. NEAR HERE)

• The discovery of predominance of long-wavelength structure in the deep mantle by imaging methods called seismic tomography has brought a paradigm shift to our understanding of mantle convection and thermal evolution of the Earth’s deep interior, with new emphasis on thermo-chemical dynamics. (FIG. 4. NEAR HERE)

• Project EarthScope, a major research effort led by the NSF is accumulating unprecedented spatial coverage of seismic and geodetic observations across North America, revealing remarkable crustal and lithospheric structures that are divulging many secrets of continental growth.

• The emergence of quantitative physics-based predictions of surface ground motions using realistic 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 is 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. (FIG. 5. NEAR HERE)
FIG. 4. Properties of a recent shear velocity 3-D earth model in wavenumber (reciprocal of wavelength) and space domains. (a) Power spectrum of model S362ANI as a function of wavenumber and depth; red is high power, blue – low. There are three regions with high power: top boundary layer (Moho – 250 km depth), transition zone (410-650 km depth) and bottom of the mantle (~2000-2890 km depth). The latter two are dominated by very large wavelength anomalies; particularly high power is in degree 2, which corresponds to a 20,000 km wavelength at the surface. (b) Shear velocity anomalies at 600 km depth, blue is fast, red – slow; the range is ±2%. High velocity anomalies in the west Pacific and under South America–Atlantic correspond to accumulation of subducted lithosphere in the transition zone. (c) Shear velocity anomalies at 2800 km depth; the scale range is -/+3%. At this depth a very large proportion of the total power is concentrated in the longest wavelength; particularly degree 2. There are two low velocity regions (the African and Pacific “superplumes”) and a continuous ring of higher than average velocities. This would correspond to degree-2 convection. None of the current numerical models of mantle convection predict such a picture; it may require development of a new paradigm of flow in the mantle. (From Kustowski et al., 2008)
FIG. 5. Rupture zones of the December 26, 2004 and March 28, 2005 great Sumatra earthquakes. The 2004 event was magnitude 9.15, the largest event since the 1964 Alaska earthquake, and it generated a tsunami that claimed over 225,000 lives around the Bay of Bengal. International teams of seismologists and geodesists have studied all aspects of how the rupture spread over the fault and how slip varied along the subduction zone, including afterslip which occurred for several months after the event. (Courtesy of C. J. Ammon).
Continued health and vigor of Seismology requires Federal and Industry attention to critical foundations of the discipline, including sustaining and expanding data collection and dissemination infrastructure, providing access to high-performance computational resources, attracting diverse, quantitatively-oriented students to the basic research efforts in the discipline, and fostering interdisciplinary communications and interactions to study complex Earth systems. In order 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 topics for the next few decades and associated infrastructure needs essential for making progress on these topics.
Grand Challenges for Seismology

Grand Challenge 1. The Physics of Fault Failure

Stresses resulting from the relentless relative motions of the Earth’s plates are relieved mostly as slippage along faults. The most spectacular, and sometimes dangerous, release of stresses occurs in earthquakes, in which energy stored up over hundreds to thousands of years is released as faults slip within seconds and radiate seismic waves. Recent observations reveal a richness of other fault slip behaviors, from faults that creep silently without apparent resistance, that slide sporadically chattering as they go, to others that slide at super-shear velocities emitting seismic shock waves. The rapid, radiating fault slip represents a hazard unparalleled in the population potentially affected and currently, in the lack of clear short-term evidence of an impending event. Nonetheless, great strides have been made in understanding how and when faults are likely to fail, such that seismic hazard assessments useful at scales appropriate to planning, mitigation, and response within an urban area are now reality.

Those who study fault failure do so within the conceptual framework of stress renewal – a budgeting process in which strain energy supplied by plate motions must balance with its release primarily as slip on faults. While convenient for forecasting, questions have arisen about the spatial and temporal scales over which the supply and release must balance and even about the appropriateness of the framework itself. An example of the latter is the recurrence of large intra-plate earthquakes, evident in the geologic or ‘paleoseismic’ record spanning thousands of years, where no relative motions currently provide a supply of strain energy. On time scales of a few years, in which a fault experiences a single earthquake and it and its immediate environs re-equilibrate, we can now measure and model the suite of changes that occur and infer cause-and-effect relationships.

As instrumentation and computing capabilities have advanced, the boundaries between disciplines relevant to understanding the physics of fault failure have become murkier. For example, the characterization of slow, steady, aseismic fault slip has been purview of
GPS studies while studies of rapid, radiating slip belonged to seismology. However, the expanding bandwidth of instrumentation in both disciplines has led to the recognition that faults slip at a continuum of rates. New networks of strainmeters and tiltmeters are likely to take us the next leap forward in improved sensitivity, particularly in on scales between traditional seismology and geodesy.

If one wants to understand the rapid slip that occurs during earthquakes, seismology still and likely will always provide the highest resolution tools for peering into the rupture process. Fault slip is controlled by frictional properties of the fault surface as one side slides past the other, and these properties change spatially and evolve temporally. Fault surfaces and their frictional behaviors vary tremendously, from smooth mature faults filled with wear material developed as hundreds of successive earthquakes grind the rock, to those with geometric irregularities that obstruct motion, and perhaps some with fluid inclusions that dramatically alter the frictional properties. Regional catalogs of the locations of tiny to moderate earthquakes, accurate within tens of meters, reveal this diverse frictional behavior among faults and even within a single fault surface. On some faults the heterogeneity is best described statistically and appears fractal, and on others it is highly organized; e.g. streaks, persistent alignments of small earthquakes on a larger fault, appear to be striations in the frictional properties that align with long-term stressing directions. A surprising fraction of fault surfaces slip repeatedly at intervals indicating some just-broken faults heal on extremely short time-scales (days to weeks) and elsewhere may take orders of magnitude longer.

[CA seismicity figure]

While not dangerous themselves, the basic knowledge of when and where the thousands of small earthquakes occur provides key constraints on when and where large damaging earthquakes are most likely. This map shown on the left displays the ‘where’, or epicenters (black dots), of 81,679 earthquakes that occurred along the San Andreas fault system between 1984 and 2003, with magnitudes as small as 0.5 and most <3.5. Dark lines indicate mapped fault traces. Large computers and clever processing techniques
now enable datasets comprised of hundreds of thousands of earthquakes to be located accurately enough (within fractions of a kilometer) to illuminate physically significant patterns. In this example, the distribution of epicenters reveals a tremendous diversity in the properties of faults and how these change in space and time. Earthquakes relieve accumulated stresses when faults break and their surfaces slip within seconds, radiating seismic waves. This map shows that some faults readjust nearly continuously by slipping in tiny increments and thus, produce high rates of small-magnitude seismicity. In contrast, entire or segments of other faults sit completely locked-up or ‘stuck’ and silent, presumably storing up stresses to be relieved some day in a big earthquake. Other faults behave in between these continuously creeping and completely locked modes. Also noteworthy are the numerous earthquakes that occur where no faults are mapped at the surface, suggestive of hidden hazards and a more complex network of faults than can be inferred from the surface geology alone.

The location of one earthquake relative to another can be estimated with even greater accuracy (within meters) than absolute locations. This accuracy is comparable to the dimensions of the fault segments that break in the smallest catalogued earthquakes. Relative locations combined with knowledge of when the earthquakes occur provide valuable constraints on how rapidly the same fault can rupture, restrengthen, and
accumulate sufficient strain energy to break again. For the region of central California shown in the map on the right, 12% of all earthquakes analyzed occurred on faults that failed multiple times during the 19 years of the study period. Most of these ‘repeaters’ included only two earthquakes and are geographically widespread (colored circles on the map, with the number of repeats indicated), and sequences of ten or more repeated failures seem to concentrate along the faults known to creep continuously. This suggests that tiny patches of fault on these otherwise creeping faults strengthen very rapidly – within days to a few years – so that they can become restressed by the nearby ongoing slip. Even recurrence times of the order of a decade are remarkably short. Overall, a picture emerges in which both the processes of strengthening and stressing appear to operate on expected time-scales of many tens to hundreds or thousands of years, but also on significantly sped-up scales on a significant fraction of faults.


All these variations significantly impact the characteristics of waves radiated, which in turn interact with the built environment. In addition, deformations carried by these transient waves and the permanent deformations nearby a just-slipped fault clearly affect the likelihood of future earthquakes elsewhere. Patterns of these deformations now may be measured or modeled and used to forecast the spatial and temporal distributions of aftershocks. Dense, yet widely distributed recordings of the radiated seismic energy now permits the strain energy budget balancing to include estimates of the energy lost to heat, fracturing new rock, and other processes.

Small aperture seismic arrays, particularly those atop major faults, and clever array-processing analyses are beginning to serve effectively as movie cameras capturing the initiation, growth and stopping of fault ruptures. These constrain physics-based
theoretical models that may now be used predictively, at least in a probabilistic sense. We are close to understanding what controls the direction in which a fault rupture may propagate, the prediction of which would allow us to anticipate where radiated waves will be focused and shaking amplified. Seismologists can now tackle questions needing extremal rather than mean answers, such as what are the maximum earthquake ground motions that a nuclear waste repository might experience in its 10,000 year lifetime?

Among the most exciting Earth sciences discovery of the decade has been that of the coupled, and in some places predictably repeating phenomena of slow slip and tremor. Originally thought unique to subduction zones, it is now clear that these phenomena occur in other environments, with many places remaining unexplored. Scientifically consensus is building that the slow slip represents a frictional behavior intermediate to that of being completely locked (stuck) until rapid slip takes place in earthquakes and of steady, seismically silent creep. Tremor, a low-level seismic rumbling, clearly correlates with the slow slip but its cause remains a mystery. The manner in which both slow slip and tremor grow in amplitude and duration appears distinctly different from the way earthquakes scale, but whether the distinction is sharp implying two fundamentally different failure processes or is diffuse suggestive of a continuum remains to be determined. For the public these phenomena highlight the thrill of unanticipated discovery and suspense of what’s yet to learn, while being tangibly observable. Moreover, characterizing where and when slow slip and tremor happens effectively can provide a map of the portions of major faults likely to fail as earthquakes, with resolution and in places otherwise impossible.

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SIDEBAR – RAPID WARNING

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 that you could get under that table, move away from that bookcase or that brick wall. Your train could slow and stop and the highway meter lights could turn red. Nuclear power
plants could drop the 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.

Warning of pending volcanic eruptions and coming tsunamis are more familiar. Like earthquake warning, they use real-time geophysical networks to monitor earthquake activity and issue warnings when a potentially hazardous event is underway. Earthquake warning is not earthquake prediction. The intent is not to provide hours, days or weeks of warning by predicting when and where an earthquake will occur. Earthquake prediction is not something that most earth scientists think will be possible in the foreseeable future. Rather, earthquake early warning involves rapid detection of the beginnings of an earthquake, assessment of the likely shaking and then subsequent warnings to those in harm’s way. Earthquake early warning is here today.

In October 2007 Japan launched the first national earthquake warning system. The system builds on four decades of development culminating in a network of over 1000 seismic stations linked together to detect earthquakes underway, and issue warning to the public. Taiwan, Turkey, Mexico and Romania also have warning systems in place, many other countries have systems under development. In the US, the California Integrated Seismic Network is testing warning systems in real-time today. The October 30, 2007 Mw 5.4 earthquake near San Jose provided a proof-of-concept (see figure). The test-system detected the event and determined an accurate estimate of the hazard using just three seconds of data, and before the shaking was felt in San Francisco.

Further development of the warning methodology is necessary in order to build a robust system. The challenges include improved methods for the largest magnitude earthquakes. Promising development is underway to map the distribution of slip on faults in real-time using seismic and geodetic networks. Dense geophysical instrumentation in earthquake source regions, with rapid and robust telemetry, will also be needed.
FIG: Earthquake warning AlertMap showing the predicted distribution of ground shaking for the October 30, 2007 Mw 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. The surrounding photos show various applications of rapid warning and hazards generated by earthquakes.

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Sidebar:

New ‘cybershake’ probabilistic earthquake hazard maps bring together nearly all facets of the state-of-the-art not only in the field of seismology, but in relevant aspects of geology, geodesy, geotechnical engineering, and physics. Such maps are “where the rubber meets the road”, translating research into real-world products that impact society daily. Probabilistic earthquake hazard maps provide long-term forecasts needed for building codes, setting insurance rates, urban planning, and other public and commercial
policies and activities. Among other applications, the City of Seattle is using these new maps of Seattle to prioritize their program to mitigate the hazard posed by unreinforced masonry buildings, which are highly vulnerable when shaken by seismic waves.

Probabilistic hazard maps account for the shaking due to all known earthquake sources that might impact a region and their varying likelihoods of occurrence. A new breed of ‘cybershake’ maps, like the one shown for Seattle, use simulations the radiation of seismic waves from realistic fault models and how they propagate in high-resolution, 3-dimensional characterizations of the subsurface derived from recent seismic imaging studies, and geologic surveys of surficial materials. These physics-based simulations reproduce much of the complexity apparent in real earthquakes, with the range of possibilities captured by averaging hundreds of simulations – possible now using advanced computer systems and modeling algorithms.

This probabilistic map tells us that Seattle has a 10% chance of experiencing the ground motions at least as big as those shown, within a 50-year time window. The same inputs may be used to generate other maps or forecasts for different probabilities or time intervals. While other measures may be used, in this map ground shaking levels are
measured in term of the accelerations in units of ‘gravity’, associated with waves that oscillate with a period of 1 second. The US Geological Survey and its partners generated these maps for Seattle, and multi-institutional efforts to produce similar maps are underway for several regions of California.

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Sidebar: ETS

The implementation of the Earthscope strain, seismic, and geodetic networks in Cascadia has lead to views of the evolution of slow-slip and tremor with unprecedented resolution. Scientists can now address questions about how these phenomena may be linked to one another and to the larger-scale dynamics of plate boundaries. This three-dimensional view of western Washington and Vancouver Island shows the plate interface between the Juan de Fuca and North American plates (light grey surface; black surface is the Moho of the subducting plate). In this region of Cascadia approximately every 14 months the interface slips slowly; in 2007 signals on continuous GPS receivers reflect slow slip across a patch of the plate interface (dark grey shading), concurrent with thousands of seismically observed tremor bursts. Although the depth of the tremor sources remains uncertain (circles, color coded by their dates of occurrence), the temporal and spatial coincidence of the tremor sources with the slow slip clearly indicates a physical link between the two phenomena. The tremor activity clearly migrates, and analyses of strainmeter data are beginning to show a migration of slow slip, which although not yet definitive, appears to track the tremor path.
The greatest density of population in Cascadia sits atop directly and just to the east of slow slip and tremor in Cascadia. As of 2007 the prevailing idea was that the plate interface was locked and storing strain energy within the area contoured, to be released in the next great M>8 Cascadia earthquake. The degree of locking diminishes as the plate interface deepens, going from 60% just at the coast to the most inland contour at 20%. Most models of slow slip explain it as the region that is transitional between where the plate is locked and where it is sliding continuously. This new picture of slow slip and tremor suggests the prevailing model of the rupture area of the next great Cascadia earthquake needs revision, that the locked zone likely extends significantly deeper and inland, closer to the population. The potential to map the properties and slip behavior of the deeper reaches of the subduction interface fault with the resolution afforded by these slow slip and tremor maps was not unanticipated, but will undoubtedly improve the accuracy of earthquake hazard estimates affecting millions of people.

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Sidebar: **Earthquake Prediction** - Predictability of earthquake processes on various time and length scales – from probabilistic to deterministic, from stability of fault strength/asperities to chaotic behavior, rupture direction to maximum slip, aftershocks to triggering, ETS periodicity to fault zone healing, forecasting to prediction (JG, RA)
Grand Challenge 2. **Stress and Rheology in the crust and mantle**

**Seismology Grand Challenge 2: Stress and Rheology in the Crust and Mantle**

The basic ideas of plate tectonics are elegant in their simplicity and remarkable for the range of geologic processes they explain. Most large-scale features and phenomena within the Earth’s crust and uppermost mantle may be explained as consequences of the relative motions of the plates. However, a complete understanding requires accounting for the mass that is moved and how it deforms, or equivalently the linkage between the strains and kinematics (motions) and the forces or stresses that shape our environment. Rheology describes the linkage between the stresses and strains, and even for the same materials, it often varies depending on the temporal and spatial scales considered. Motions and strains may now be measured extremely precisely on many scales using vast networks of GPS, strainmeters, and tiltmeters, but stress can thus far only be inferred. Knowledge of lithospheric stress is essential to understand the forces driving both plate boundary and intraplate deformation, as well as the more localized redistribution of stress that accompanies the earthquake cycle.

Global maps of earthquakes tell us immediately that the plates do not slide frictionlessly past one another, but rather get stuck along their boundaries. Stresses accumulate mostly along the boundaries and occasionally within the plates. The release of stresses occurs on a complex network of faults that interact, with the failure and slip on one fault perturbing the stresses and material properties on and around other faults. The operation of seismic monitoring networks in stable, spatially dense configurations and innovative analyses of the seismograms they provide are yielding new ways of monitoring changes in stresses and material properties. These new ‘meters’ come in the form of temporal variations in seismic coda (scattered energy) characteristics, in wave velocity changes measured from earthquakes that rupture the same fault repeatedly, and ubiquitous ‘noise’ or ambient ground vibrations radiated from non-tectonic sources.

Aftershocks provide the clearest, most common example of interacting faults, and since the 1992 Landers earthquake few would argue that one earthquake can change the
likelihood of another elsewhere (‘trigger’) at distances of tens to even thousands of kilometers.

[Denali sidebar]
The most informative way to learn about earthquakes is to observe them in action. The 2002, M7.9 Denali, Alaska earthquake was an extraordinarily information-rich event, and observations of the event continue to surprise and inform Earth scientists. The figure below needs no statistics or seismological training to be convinced of the cause-and-effect. The waves radiated from the Denali earthquake (top panel) traveled 3000 km to the area near Bozeman, Montana where they shook and deformed local faults causing them to fail as tiny earthquakes. The signals from these local earthquakes (bursts in the second panel above green arrows) are obvious when the much lower frequency waves from the Denali event are eliminated from the seismogram by filtering. A closer look at one of these bursts (lower panel) confirms that they are from local earthquakes triggered by the Denali waves. The reason why these local earthquakes continue long after the waves have passed remains an unsolved mystery.

By combining both seismic and high-rate GPS data from the many instruments throughout western North America, scientists mapped the geographic variations in the Denali waves, revealing a focusing of wave energy along the same strike as the faults that broke in the earthquake. While seismological theories easily explained how this focusing occurs as the waves pile up in front of the propagating rupture, the sharpness and resulting amplification were extreme, along a swath extending from Alaska into California. These large waves triggered earthquake sequences like those near Bozeman, caused seiches in lakes and swimming pools well below the US-Canadian border, and triggered bursts of tremor that likely originated below the earthquake-generating portions of the subduction interface in Cascadia and transform boundary faults in California.

Observations near the Denali earthquake also reveal remarkable features. The few instruments capable of recording on-scale the strongest near-fault shaking recorded enormous ground motions. These recordings, seismograms from more distant sites, and
state-of-the-art modeling showed the rupture proceeded at typical speeds along some stretches of the fault and along others at ‘super-shear’ speeds some thought impossible. This variation in rupture velocity appears to correlate with aftershock patterns, again illustrating a complex set of interactions between faults. The modeled Denali earthquake faulting process, and geologic mapping of surface breaks confirm that multiple fault strands broke in a continuous rupture. This observation provides both strong constraints on the forces that drive ruptures, causing them to jump from one fault to another. It also presents a challenge for predictive modeling of large earthquake in highly faulted regions, indicating a multitude of possible future rupture scenarios may need to be explored.

Despite the ubiquity of aftershock sequences, numerous theories exist to explain their long-lived temporal behavior. New insights have begun to emerge however, as records
of seismicity rates are combined with measurements of the slow deformation associated with post-earthquake re-equilibration from GPS and strainmeter instruments, all operating in the same region. These all show remarkably similar temporal signatures that, with the help of numerical models, significantly narrow down the number of types of plausible rheology and stress transfer mechanisms.

Many of the limitations on what can be learned observationally posed by the slow pace of geologic processes may be overcome using computer simulations of the behavior of complex, interacting fault networks embedded in ever-more realistic Earth models. Earthquake ‘machines’ that incorporate much of the Earth’s complexities and the physics that govern its behaviors employ the latest in ‘peta-scale’ computing. Simulated catalogs spanning many thousands of earthquake cycles will provide the basis for ever-more robust earthquake forecasts.

In addition to these macroscopic views, an understanding at the small-scale also is necessary. Drilling is one means of sampling otherwise inaccessible fault surfaces at depth. Drilling provides in situ measurements of active fault properties at seismogenic depth, as well as samples of fault material for further study in the lab. Information on constitutive properties of the active fault, composition and distribution of pore fluids along the fault zone, quantity and properties of fault gouge, and dimensions of the seismogenic zone, factor into studies of crustal stress and earthquake stress transfer. Rapid post-earthquake response drilling close to fault zones is now being done to understand how ruptures start, progress, and stop. Well breakouts can be used to determine stress orientation, and the vertical variations of stress and strength in the vicinity of the borehole can be measured directly. Continental drilling provides in situ measurements of stress and physical properties of the upper crust.

To fully understand, and ultimately to predict, how the plates move and deform, a big-picture perspective is needed. What is the setting within which not only fault systems operate, but also in which mountains, basins, high plateaus, etc. are built? A new frontier is developing ways to use of all seismic data, including the ‘noise’ in between the much
less frequent well-defined wave types emitted from earthquakes, to improve the resolution of seismic images, particularly in places that previously were poorly characterized. Seismically derived images constrain models of lithospheric structure, such as the depth and topography of the Moho, vertical and lateral heterogeneities in lithospheric rigidity, and identification of the brittle/ductile transition. 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. This can give us a better handle on the forces driving some of the deformation away from plate boundaries. [Sidebar on New Madrid?]

Studies of anisotropy, imprinted directionality in the structural fabric that causes seismic shear waves with different orientations to travel with different speeds (and thus can be measured), are providing constraints on the long-term history of strain in the lithosphere. For example, anisotropy measurements permit estimation of the magnitude and orientation of shear strain in the asthenosphere and thus, inferences about the orientation of the shear stress at the base of the lithosphere. When coupled with geodynamics and geodesy long-standing questions about how sublithospheric mantle flow couples to and stresses the base of the lithosphere can be addressed. In many cases mantle anisotropy is used as a proxy for flow or deformation. These studies explore how flow affects plate motion and the transfer of stress to the lithosphere.

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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. This information is used as the design criteria for new construction. A typical building may be designed to withstand the estimated peak ground acceleration with a 2% probability of exceedance in 50 years. A wide variety of seismic data is the basis for these maps including the distributions of known faults, the history of earthquake activity, regional strain rates, the likely intensities of ground shaking for all possible earthquakes,
and surface amplification effects. The development of these maps, and their adoption as design criteria by the engineering community, will save thousands of lives in future earthquakes.

The catastrophic nature of structural failure at critical facilities, like nuclear power stations, requires construction to a high standard of ground shaking tolerance. They must withstand the stronger ground shaking anticipated with much smaller probabilities of occurrence, i.e. resulting from larger events with longer recurrence intervals. The design lifetime of long-term waste repositories also requires designs for earthquakes with a much smaller probability of occurrence. Our historic records only capture the most recent earthquake activity and often do include the largest possible events in any given region. We must therefore extrapolate our hazard curves out to lower probabilities and stronger ground motions.

The challenge is that extrapolation of existing hazard curves implies ground accelerations and velocities that have never been recorded for any earthquake worldwide. The seismic records that we do have for larger earthquakes also show non-linear effects for strong ground motion that cause saturation of ground shaking intensity and therefore a limit on the strongest ground shaking. New methods are needed to test and constrain the nature of this saturation.

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 capturing the very small-scale near-surface structure. These models must then be validated and verified. This requires multiple modeling approaches and additional constrains respectively. Significant progress has been made on both fronts in the last few years. 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 formation can be used to limit ground motion on geologic time scales.
Figure: Probabilistic seismic hazard curve for Yucca Mountain, Nevada. It shows 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 is $4 \times 10^{-4}$/yr. The design criteria for the proposed long-term nuclear waste repository at Yucca Mountain is $1 \times 10^{-8}$/yr. The mean PGA at this P.E. is eleven times the acceleration of gravity. 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 Chūetsu Earthquake. The reactor caught fire and there were leaks of fluids and gas. The ground motion in this earthquake exceeded the design criteria and the reactor, Japan’s largest, remains closed.

Grand Challenge 3. **Physical coupling of the atmosphere/ocean/solid Earth systems.**

Seismology can be broadly defined as the science of listening to sounds in the Earth. This includes not only the sounds coming from natural earthquakes and controlled sources, which constitute the traditional realm of seismology, but, increasingly, detailed study of signals from both long-recognized and recently discovered 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. Scientific challenges include:

- *Improved understanding of the coupling mechanisms between ocean waves and seismic waves over a broad range of frequencies.*

   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 accumulated over several decades. It has now been established that the primary sources of the “hum” are in the oceans (figure x), and are related to mid-latitude winter storms that generate strong ocean waves which couple to the ocean floor via non-linear mechanisms that are not yet well understood. It is not clear yet how and where the coupling occurs, whether it is near the coast or in the deep ocean, and how it relates to the global microseism noise field at shorter periods (5 to 30 s). The ocean wave origin the microseism was demonstrated in the 1950’s, but for decades, its study was pursued by few researchers, and 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 oceans. The renewed interest in elucidating the relation of Earth’s seismic background excitation across hum and microseism periods to ocean processes has happened concurrently with the realization that the background excitation of the microseism could be exploited to extract crust and upper mantle structure *(see section X)* through correlation techniques. Characterizing sources of Earth’s ambient noise across the microseism and hum period band, their locations, and the fluctuations of their amplitude with time are now of interest to a large,
multi-disciplinary community, with applications ranging from the study of Earth structure, to effects on floating sea ice, to coastal oceanography and the effects of long period ocean waves (infragravity waves) in harbors.

- **Characterization of historical and present changes in ocean wave activity and its connection to climate change.**

Global warming affects broad-scale atmospheric circulation patterns, resulting in increasing storm duration and intensity. The remarkable way in which microseismic and hum noise tracks ocean storms indicates that seismic records may provide a new and valuable integrative window into climate change at scales not otherwise accessible. 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. Likewise, potential uses of T-phases (seismic sound in the oceans) to monitor warming of the world’s oceans should be investigated, which will require a better understanding of their excitation.

- **Development and validation of new methods for quantifying ocean mixing and turbulence.**

While ambient seismic noise relates to ocean dynamics at rather high frequencies by oceanographers’ standards, another stunning discovery was recently made when analyzing record sections acquired through marine reflection seismology profiles. While the primary goal of these experiments is to investigate sedimentary and basement structure below the seafloor, the recovered images also clearly detect layering and mixing in the water column. These images, which provide unprecedented horizontal resolution of thermal boundaries, have a wide range of potential applications. One of the most exciting is the possibility of deriving quantitative estimates of internal wave energy and turbulent mixing from seismic images that can help illuminate thermohaline circulation, which plays a key role in climate and natural sequestration of atmospheric carbon (see Imaging Internal Ocean Structure sidebar).
- **Glacial seismology.**

Investigating the origin of the “hum” also led seismologists to search deeper into the background long period seismic noise. This soon led to further discoveries of “exotic” sources, spinning off another new and vibrant interdisciplinary field, that of glacial earthquakes and related phenomena. Key types of these unusual kinds of earthquakes largely escaped attention until recently, because they do not generate short period (1-10 s) seismic waves that are the target of standard earthquake detection and location algorithms. Now they are turning seismologists into glaciologists and vice-versa, holding much promise for tracking and understanding how our polar ice sheets are falling apart as global warming progresses. Understanding causes and broader implications of glacial earthquakes will require applications of classic seismology developed from the earthquake field, combined with new modeling incorporating glaciology, oceanography, and other fields. 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 (see Cryoseismology sidebar).

- **Infrasound and ionospheric waves**

Seismic sources within the solid earth generate waves that propagate not only through the ground but also through the oceans (e.g., tsunami and T-phases), or through the atmosphere (e.g., infrasound generated by volcanic eruptions and earthquakes), or even into the ionosphere, where remote sensing using GPS holds potential for new ways to characterize the source of large earthquakes. An explosion or disturbance near the surface of the Earth will produce both seismic energy, detectable on sensitive broadband seismographs, and infrasound energy, best observed on microbarographs or, at high frequencies, by microphones. Infrasound can be caused by meteors or comets exploding several kilometers above the Earth’s surface, or even by changes in atmospheric pressure causing 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 gain understanding of atmospheric structure and its variation with time at spatial and temporal scales inaccessible by other means. It can also help locate and characterize man made and natural sources of these waves and monitor their hazards, including the key application of nuclear test monitoring (see Monitoring sidebar).

Figure 1 a. Comparison of seasonal variations in the distribution of long period “hum” sources (top) from array beamforming using very broad band seismograph (STS-1) recordings, and significant wave height in the oceans (bottom) from satellite observations, showing how hum sources track with the location of the strongest winter storms. In the top panel, arrows point to the area of maximum hum energy generation, and the color bar indicates areas generating hum with amplitudes larger than 85% of the maximum. 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). 
*After Rhie and Romanowicz (Nature, 2004).*

Figure 2. Left: Infrasonic sources monitored across Europe using regional infrasound records for the time period 2000-2007. Right: non-earthquakes reported events in seismic records for the overlapping period 1998-2005. After Vergoz et al. (2007) and Godey et al. (2006).

**Sidebar: Cryoseismology** –

Solid Earth, glaciological, oceanographic, atmospheric, and biological, research in the Arctic and Antarctic has expanded notably during the past decade and is, at this writing,
being advanced in International Polar Year (2007-2009) activities incorporating over 50 nations. Seismology in polar regions offers unique advanced capabilities to: 1) fundamentally constrain continental history and deep Earth processes, as well as key geophysical variables (e.g., geothermal heat flow and its effects on ice cap evolution) in these relatively unexplored regions, and 2) identify and study essential dynamic processes associated with the cryosphere’s ice caps, glaciers, and floating icebergs and ice shelves. Strong interdisciplinary science motivations, coupled with dramatically improved capabilities to site seismographic instrumentation in extreme cold environments recently spearheaded by the IRIS PASSCAL and GSN programs, has uncovered novel scientific opportunities that are currently being envisioned and explored by seismologists, oceanographers, and glaciologists under the support of NSF OPP and other sponsors. Cryoseismic research offers novel quantitative studies of ice processes that in many cases are known or suspected to show sensitivity to climate change. Work presently being proposed includes a high-quality seismographic network for Greenland and new deployments to study ice shelf stability/disintegration. The floating ice shelves at the termini of major glacial systems are of critical importance because they are known to buttress inland glaciers, thus inhibiting flow into the oceans and attendant sea level rise. The generation, transport, and glacial effects of subglacial water are a key interdisciplinary area of study that has wide relevance to processes affecting ice sheet stability in both Greenland and Antarctica.

Recent cryoseismological avenues of research include: 1) Imaging the west Antarctic mantle using techniques proved on other continents to constrain tectonic evolution of the continent and the history of ice cap changes and future evolution. The stability of the west Antarctic icecap is of particular interest. Its grounded ice volume is the equivalent of a 6-meter change in sea level, and it may be especially subject to destabilization because much of its base lies below sea level. 2) Studies of tidally modulated ice stream surging in west Antarctica. 3) Iceberg seismic and ocean acoustic tremor and breakup processes arising from collisions and wasting of Earth’s largest icebergs. Here new data recovered from both land- and iceberg-sited seismographs is illuminating the nature and significance of ice-ice collisions and ice-seafloor grounding, and iceberg breakup in the
Antarctic. 4) Regional remote detection of glacial calving via sea swell “minitsunamis” using broadband seismometers deployed atop giant tabular icebergs. 5) Monitoring and study of a newly recognized class of globally detectable slow glacial earthquakes from major tidewater outlet glaciers in Greenland. These glaciers, among the largest on Earth, are undergoing rapid retreat and other change due to the increased presence of basal meltwater and other climate-driven changes. Recent evidence suggests that the newly discovered Greenland seismic sources are associated with both terminus calving and retreat processes in these glaciers, with mechanism details and linkages to the larger glaciological and oceanographic systems areas of active research.

Recent examples of novel glaciological signals studied with seismology. (1) Cryoseismic tremor in the Ross Sea region resulting from ice-ice and ice-grounding collision and wasting of Earth’s largest icebergs; a) MODIS satellite view of icebergs colliding near Ross Island; b) IRIS PASSCAL seismographs installed in 2004 atop iceberg C16, which
was aground near the northern coast of Ross Island; e) Vertical seismic displacement (mm) recorded over a multi-hour period on 19 January 2004 of tremor arising from collisions between tidally-drifting B15A and C16; d) spectral depiction of the evolution of tremor with time near the aseismic “eye”, showing the harmonic structure of the tremor; e) expanded view of the tremor, showing the individual icequake pulses making up the tremor at its finest scale. After MacAyeal et al. (2008). (2) Slow icequakes from the Whillins Ice Stream in west Antarctica. These ice streams are the principal mechanisms that transport ice from the vast west Antarctic Ice Cap to the floating Ross Ice Shelf. Coordinated seismic and GPS observations demonstrate that ice flow (directions shown from GPS measurements in red) is episodic, occurring in approximately 40 cm slips that are triggered twice per day by ocean tides. The area of slip is approximately 200 by 100 km, and each event is thus equivalent to a slow earthquake of approximately moment magnitude 7. The slip nucleates repeatedly at Ice Rise a, a feature that is controlled by sub-glacial geology. After Wiens et al. (2008). (3) 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. After Ekstrom et al. (2006).

References


Sidebar: Imaging the fine structure of the oceanic thermohaline circulation - an example of seismological serendipity.

The image shown below was gathered during routine seismic profiling of sub-seafloor structure off the Grand Banks on the R/V Ewing, but, instead of showing structure within the sediments, it reveals 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 is a slow process that limits the volume of ocean that can be sampled and has limited 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 the ocean, 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.

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Grand Challenge 4. **Critical interfaces and seismic waves in the near-surface environment.**

The near surface is the critical interface in Earth system science between the solid planet and the hydrosphere, oceans, atmosphere, and biosphere. Humans live on the surface of Earth and interact with the deeper planet through the near surface. Most earth hazards are strongly influenced by near-surface materials, whether the ultimate cause arises from the deep earth, atmosphere-ocean systems, or human activity. In turn, many of these hazards change the land upon which we live and leave behind a record of those changes. Near-surface sediment deposits are the youngest on the planet and therefore record the most recent changes due to active processes such as climate change, floods, landslides and earthquakes. Most of our water, energy, and mineral resources lie in Earth’s sub-surface at depths of meters to a few kilometers and are created or affected by near-surface processes. The study of Earth’s near surface is therefore a crucial part of creating a sustainable environment for humans to live in.

While well established and thriving, near-surface geophysics is on the verge of explosive growth because of the pressures being put on our environment. While the near surface is accessible to drilling and excavation, it is explored in a cost-effective and non-invasive manner by exploration geophysics. Seismology provides several imaging methods that work well in near-surface environments, including the use of refracted, reflected, and surface waves.

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 seismic shear-wave studies without disturbing the site. Surface waves can be used for such studies in urban areas utilizing ground
shaking from urban 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 a mitigation strategy. Microearthquakes along the sides and bottoms of landslides can potentially be used as a proxy to monitor creep using seismic methods.

Earthquakes occur on deep faults but the strength of ground shaking is heavily influenced by shallow soils and geologic structures. Characterizing the seismic properties of shallow deposits is crucial to assessing the risk from strong ground motions during earthquakes. Strength of ground shaking is determined in large part by the properties of shallow soils, the potential of those soils to liquefy, and the underlying geologic structure such as sedimentary basins. Seismic wave amplification (site response) is often estimated from seismic shear-wave velocities in the shallow strata as determined by refraction measurements and/or surface wave analysis. Models of earthquake ground motions rely on accurate seismic wave-speed models of the subsurface, particularly of sedimentary basins which are readily mapped using seismic refraction, reflection, or earthquake tomography methods. The potential for a soil to liquefy may also be discernable from its seismic properties such as shear-wave speed and attenuation. Ground rupture can be predicted by mapping faults at the surface surface and in the subsurface through offsets in shallow seismic layers. Density, compressional-wave speed, porosity, and water saturation also play important roles in determining ground shaking and ground failure during earthquakes. Challenges lie in understanding how to relate seismic properties to the nonlinear deformation that occurs during strong ground shaking and liquefaction.

In the coming decades, clean fresh water will become one of the most precious resources on the planet. Although surface waters are more accessible, about half of the fresh water used in the USA today comes from groundwater. Groundwater reserves are about two orders of magnitude larger than surface fresh waters. [NOTE: the previous three sentences were also included in my Resources Sidebar; they should be deleted in one of the two locations.] 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. In addition to delineating aquifers in sediment and sedimentary rock, seismology can be used to map fractured rock aquifers in regions with more limited groundwater supply. Compartmentalization or connectivity of reservoirs 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.

The successful application of near-surface seismology to these problems relies on improving our technological capabilities and our understanding of near-surface processes such as wave propagation, attenuation, and the influence of porosity and fluids on seismic properties. Field tools are becoming widely available for rapid acquisition of large volumes of near-surface seismic data, but the methods need to be made more cost-effective, at the highest possible resolution, with more automated analysis. Geophysicists also need to learn how to produce, and communicate, the parameters desired by engineers so that the advantages of seismic methods will be more widely adapted.

The near-surface is the easiest and least expensive portion of the earth to image due to its proximity to seismic sensors and controlled sources. For this reason, the resulting images can have remarkable resolution, sufficient for imaging soil properties or archeological artifacts. However, the shallow subsurface can also be the most difficult to study because near-surface materials can have much larger and abrupt changes in seismic properties, have very high attenuation, and lie so close to the seismic sources that common wave modeling assumptions do not hold. Overcoming these challenges requires further research in controlled sources, survey design, physical modeling, and data analysis.

Although this report is primarily concerned with seismic methods, 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 seismic in combination with gravity, electrical, magnetic, radar, and electromagnetic induction methods has the potential for far better characterization of the shallow subsurface. Joint interpretation of diverse data sets is well established, but an important challenge is the
joint inversion of diverse data for a single consistent subsurface model. More important than determining the geophysical parameters is the direct identification of sediment, rock and fluid properties, including porosity and permeability. To date, such joint inversions have required careful calibration that appears to be site dependent. Better petrophysical models combined with innovative data acquisition and analyses may improve these methods to allow more comprehensive geophysical characterization of Earth’s critical near-surface environment.

**Figure 2**

Caption: 60-km long cross-section of the upper 200 m of the Los Angeles basin, at 100X vertical exaggeration, showing shear-wave speed. Red soil would most amplify ground shaking during an earthquake. The image was derived using surface-wave noise. (from Weston et al., 2006, BSSA --- obtained from John Louie)
Caption: Left: Seismic cross-section of a subsurface clay-bounded channel containing DNAPL (dense, non-dissolved, liquid) contaminant. Note scale is in meters. The black lines are seismic reflectors and the color is seismic wavespeed. Brighest black lines and coincident slower (redder) colors outline the contaminated channel. Center: Map of depth of seismic reflections from the top of the clay layer. Right: Horizontal slice at 10-m depth through 3-D seismic wave-speed model, clearly showing channel. (from Gao et al., 2006, Geophysics; Fradelizio et al., 2008, Geophysics --- get originals from Alan Levander and/or Colin Zelt)
Caption: Extremely high-resolution seismic reflection imaging across an active fault in Portland, Oregon. Orange seismometers were placed only 1 m apart, coincident with a ground-penetrating radar profile and trench for integrated studies. (from Liberty et al., 2003, Tectonophysics – obtain original from Lee Liberty; add a white box labeling the seismic profile)

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Sidebar: 4D imaging of carbon sequestration, (AS)

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Sidebar. Seismic imaging of proxies for past climates

Understanding Earth’s record of natural climate change relies in part on imaging the shallow sedimentary deposits that record and respond to climactic changes. In lake and near-shore settings, subtle climate changes produce changes in water level, biologic activity, and stream sediment that produce marked changes in the type and thickness of water-bottom deposits. Evidence for past climates is recorded in the layers, or strata,
layed down through time. Drilling of lake and seafloor deposits allows detailed analysis of geologic, biologic, and chemical markers for past environments, including proxies for temperature. However, depositional patterns over large areas are best mapped by sediment layering in seismic reflection data. Seismic stratigraphy at the scale of the continental margin has long been used to identify sea level through time and basin-scale deposition, and these methods can be scaled to look at very high resolution at the shallowest, youngest sediment to identify Earth climate of the past few hundred thousand years. Drilling programs in lakes and oceans are best designed through careful consideration of stratigraphic patterns mapped in 2-D or 3-D by seismic reflection. Once drilling has calibrated the physical cause and climate relevance of individual seismic reflectors, they can then be extrapolated beyond the borehole to better understand the sediment systems.

In addition to the sediment, fluids in the pore spaces between mineral grains may contain information about past climates. An important example is gas hydrates which are found at shallow depth below seafloor in water depths of 300-500 m. Gas hydrates are frozen hydrocarbon gases, predominantly methane, that occur in special pressure and temperature conditions. These hydrates trap a significant quantity of carbon and thus play an important role in the global carbon cycle. 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 resulted in massive releases of methane gas and CO2 from biologic decomposition of the methane, both greenhouse gases, into the atmosphere. The bottom of the gas-hydrate stability zone acts as a strong “bottom-simulating reflection” for seismic waves, mimicking the shape of the seafloor at a constant temperature. Seismology has played a crucial role in mapping the occurrence of gas hydrates on continental margins globally. Seismic reflection imaging can be used to map the thickness of the gas hydrate layer, the porosity and thus volume of hydrates, and the deeper fluid plumbing systems that feeds the gas. Sampling strategies using deep drilling and remotely operated vehicles are guided by detailed seismic site studies. Temporal changes in the hydrate layer may be caused by naturally episodic fluid flow events such as gas seeps, climate change, or
human extraction for energy resources, and these changes can be monitored using seismic reflection imaging.
Caption: 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. (from Trehu et al., 2004, Earth and Planetary Science Letters)

NOTE: The above pdf is a page from a document published by Lamont celebrating the retirement of the M/V Ewing. We should get a cleaner image from Anne Trehu. In particular, the BSR needs to be more prominently labeled, and the gas hydrate label on top would be better placed at the side and point to the entire layer (e.g., bracket-like arrow) – it should not be at the top.

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Grand Challenge 5. **Distribution and Circulation of fluids and volatiles in the Earth’s interior.**

Water is of fundamental importance to the evolution of the Earth, and in a myriad of ways (indeed, in a solar system perspective, it is not an overstatement to refer to Earth as the “water planet”). Water fundamentally affects the evolution of the continental and oceanic lithosphere by profoundly influencing geothermal heat flow and cooling, and contributes to processes that weaken faults, including the behavior of master faults at plate boundaries. Indeed, it is widely accepted that the fault lubricating effects of water are a prerequisite for plate tectonics to occur. Water geochemically interacts with Earth’s silicate crust and mantle in a great many significant metamorphic reactions, and fundamentally contributes to melting and volcanic processes. The melting of the mantle above subduction zones due to hydration induced lowering of the melting temperature is the primary mechanism by which mantle differentiates to create continental crust in volcanic arcs. Water filled cracks constitute a principal structural component controlling the attenuation of seismic energy in the Earth, as can be clearly seen in comparison of lunar and terrestrial seismograms (*see planetary sidebar?).*

Significant water is carried 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. More generally, water undoubtedly affects the global rheology and dynamics of the mantle in a great number of ways, many of these processes are active areas of current research. For example, it has recently been proposed that the flow of water and its interactions with mantle mineralogical phase transitions near the global 410 km discontinuity produce large regions of concentrated hydration and partial melt at these depths. 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, which constitutes approximately 1% of accessible water (the vast majority of near-surface water being either in the planet’s two remaining icecaps or in the oceans). Of this 1%, more than 95% is stored as groundwater. The recharge, flow, and storage of groundwater are heavily influenced by geologic stratigraphy and faults, and the principal imaging of these critically important subsurface structures is through seismology. Seismological processing techniques offer both the ability to image discontinuities (e.g., reflection seismology) and to establish bulk estimates of seismic velocities (e.g., tomography). The development of these techniques is ongoing, and is largely driven by improvements in data quality and spatial density, and by improved access to computational resources, and is a major area of common and complimentary interest between academic and industry seismologists at scales ranging. Similar seismic imaging techniques can, in fact, be scaled to problems ranging from shallow surveys measured a few meters in size to global imaging of the entire planet.

The formation, migration, and storage of Earth’s liquid and gas hydrocarbon, as well as geothermal energy reserves, frequently interacting with water, 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. Seismic exploration on land and at sea is a multi-billion dollar industry with major workforce needs in the near future (see Workforce sidebar).

Resources are currently being widely applied worldwide to investigate geological reservoirs for their carbon dioxide sequestration potential. Methodologies for monitoring and managing such sequestration efforts will rely critically on seismology, both to monitor spatial and temporal changes in seismic velocities corresponding to the fluid content (see sidebar on 4d Seismological Imaging of C02 sequestration), 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.

Sidebar: Exploration Seismology and Resources: Energy, Mining, and Groundwater

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.

For decades, seismic reflection imaging has been the primary tool used to delineate oil and gas deposits in the subsurface. The industry has devoted huge financial and human resources to the development of seismic methods to locate fluids and gases within porous sedimentary rocks. Industry enthusiastically adopted 3-D seismic reflection imaging more than 20 years ago to image structural and reservoir complexity, and more recently developed 4-D, or time-lapse repeat surveys, to monitor mechanical and fluid changes to the reservoir during resource extraction. Important seismic challenges and applications include: defining small-scale fluid compartmentalization caused by faulting or subtle changes in sedimentary environment (stratigraphy) in incompletely exploited reservoirs; successfully imaging new, deeper deposits beneath salt, which strongly scatters and bends the seismic waves; translating seismic reservoir properties to porosity, permeability and fluid saturation at the highest possible resolution; and 4-D monitoring of enhanced recovery engineering to track fluid flow through time.

Seismology is less commonly used in mineral exploration and development, but has great potential for growth. 3-D 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. This application is obvious, as coal lies in layered sedimentary rocks similar to those that host oil and gas. Exploration seismology is almost absent in the hard-rock mining industry in the USA. However, pioneering work in
other countries has proven valuable in mapping mineral deposits or the geologic structures that contain them. Challenges exist in adapting the petroleum industry tools to non-layered 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.

In the coming decades, fresh water will become one of the most precious resources on the planet. Although surface waters are more accessible, about half of the fresh water used in the USA today comes from groundwater. Groundwater reserves are about two orders of magnitude larger than surface fresh waters. The vast majority of this groundwater lies in reservoirs in sediment and sedimentary rock, very similar to the occurrence of oil and gas and therefore very amenable to existing seismic imaging technologies. Seismology is often used to characterize groundwater reservoirs at the basin scale, but is currently under-utilized at the well scale. As water becomes more of an economic commodity, seismology is likely to become an important player in identifying porosity, permeability, compartmentalization, and contamination in groundwater reservoirs.

Caption: Horizontal slice through 3-D seismic reflection volume showing Pleistocene delta channel deposits buried deep beneath the modern surface. Oil and gas reservoirs
can be strongly compartmentalized in such deposits. (from Partyka et al., 1999, The Leading Edge)

Caption: 3-D perspective of faulted ore-body (yellow), slice through 3-D seismic reflection volume used to find the ore-body in the subsurface (left), and wells and mine shaft (right) from a hard-rock gold mine in South Africa. This seismic image is being used to plan mining operations, replacing much more expensive drilling. (from Pretorius et al., 2000, Geophysics)

Sidebar: Workforce issues. Training of students in quantitative research skills. Needs of industry, regulatory, and monitoring agencies for trained personnel. SAGE (AS)
Grand Challenge 6. **Magma dynamics in the Earth’s Interior.**

Volcanic eruptions are some of the most spectacular and potentially 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.

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 "4-D tomography", making maps of the three-dimensional distribution of seismic velocities within the volcanic edifice and then monitoring changes in velocity with time as cracks open or fluids migrate through the cracks. Seismoacoustic 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.

Current eruption prediction methods are primarily empirically based, because we don't have enough information to really understand the physics. Why do some magmatic intrusions result in eruptions while others are confined beneath the surface? How can we better predict the volume, intensity, timing, and style of the eruption? How do earthquakes and volcanic eruptions trigger each other and how do volcanoes interact with each other producing simultaneous eruptions? 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.
In addition to the hazards posed by volcanos, 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 crust of the earth is formed. For example, two thirds of the earth is covered by basaltic oceanic crust averaging 6 km in thickness, all formed by magma rising from the mantle at spreading centers between diverging tectonic plates, and all formed in the last 180 million years.

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 (Figure 1). 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.

Beneath mid-ocean ridges, mantle flow models and low-resolution seismic tomography suggest that melt is produced in a zone more than a hundred kilometers across at depths as great as 100 km, yet nearly all of it makes its way to a plate boundary zone less than one kilometer wide at the surface. Does the melt migrate horizontally through tiny cracks and pores driven by dynamic pressure gradients in the mantle; or does it rise vertically until it reaches the overlying lithospheric plate and then flow horizontally along the sloping base of the plate back towards the ridge axis; or does it flow through an interconnected network of porous channels? Similarly, in subduction zones beneath volcanic arcs, what influence does the sinking plate have on the melt migration path? Does melt pond at the base of the crust and thicken the crust by underplating? Where is melt stored within the crust before erupting?
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. 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?

All of these questions can be summarized as the Grand Challenge of Understanding the Processes of Magma Generation, Melt Migration, Storage, and Eruption. Or Improving Predictability of Volcanic Eruptions Through a Better Understanding of Magma Generation and Transport.

To address these questions, the following infrastructure needs have been identified:

- order of magnitude increase in instrumentation on a few target volcanos of particular interest
- improve existing stations, including broadband sensors and "bomb-proof" sites near vents
- instruments on unmonitored volcanos
- additional infrasound detectors and arrays
- 4D active and passive studies
- temporary, broadband arrays to image deeper mantle structure beneath volcanic features, including improved instrumentation in the oceans
- Better linking with complementary data and investigators from other disciplines
- Open access to data from all volcano observatories
- Improved international collaboration
- Establishment of a "learning from eruptions" program
- Establishment of a USGS volcano hazards external grants program
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. Picture courtesy of Alaska Volcano Observatory/USGS.
Ocean bottom seismometer partially buried in new lava flow on the East Pacific Rise. It was part of an experiment monitoring microearthquakes that accompanied hydrothermal activity on the plate boundary and recorded increased seismicity before the eruption. Photo courtesy of the National Deep Submergence Facility, ROV Jason, Woods Hole Oceanographic Institution and the National Science Foundation.

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. Figure courtesy of Geoff Abers and Karen Fischer, TUCAN Experiment.
Schematic diagram showing water migrating off subducting plate (small blue arrows) inducing melt production (red) in the overlying mantle wedge, which then migrates upward eventually resulting in volcanic eruption. Light shaded region above the plate is the continental crust. Large purple arrows indicate direction of convergence between the oceanic and continental plates.

**Sidebar: Volcano Changes.** Noise becomes signal – noise studies of sources/propagation. Use of every bit in the data center, volcano imaging example of 4D imaging (needs writer – DS?)
Grand Challenge 7. Evolution and coupling of lithosphere and asthenosphere.

The lithosphere is the mechanically strong outer shell of the Earth and forms the tectonic plates. It consists of crust on top, and mantle below, varying in thickness from 0 km at mid-ocean ridges to perhaps 250 km under cratons—the ancient and relatively undeformed hearts of continents. It's the home to life as we know it, the reservoir for many resources upon which we depend, the boundary through which the Solid Earth interacts with the oceans and atmosphere, the source of most earthquakes, and holds clues to the evolution of the whole Earth.

The process through which the continental crust formed is uncertain. It is clearly originated from melting of a mantle source, perhaps starting as early as Hadean times. The composition of the crust is more silicic than a simple product of mantle melting; thus it seems the mafic component of the crust has been disposed of in some way, possibly through processing at subduction zones or delamination of the heavier mafic component.

Zircon ages suggest crustal growth in the Archean was not uniform, with, for example, spurts of growth at 3.3 and 2.7 Ga. By 2.7 Ga, many cratons seem to have stabilized by the formation of large amounts of compositionally buoyant and viscous mantle lithosphere that isolates the cratons from mantle convection. The cause of the melting that has stabilized the cratons is uncertain; various geochemical studies suggest either cratonic mantle melted in Archean subduction zones to accrete onto a cratonic core, or deep high-temperature plume-like melting occurred. Subsequent to this melting, some sort of silica enrichment substantially rejuvenated some cratons. The source of this enrichment is still not certain; however, but some studies suggest silica enrichment may be a seismically observable feature. In general, cratons are high velocity features in tomograms. This may be due to their cold temperatures, compositional effects, grain size, or other effects.

After Archean times, continents increased in size during Proterozoic accretion events, and studies of lithospheric velocity discontinuities occasionally show that these accretion
boundaries subsist over time and may modulate subsequent deformation. The lithosphere and crust also seems to destabilize from time to time, forming “drips” in which the dense portion convects away, such as imaged currently under the Sierra Nevada. These instabilities may play important roles in the formation of continental basins, the loss of mafic components in the crust or upper mantle, and the erosion of cratons. Small-scale convective instabilities may also play an important role in melting within continents, eroding geochemically old mantle, and producing 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, such as imaged in the LITHOPROBE and numerous Continental Dynamics projects, and features seem to persist over billions of years (see Figure 1).

Unlike continental crust, oceanic crust is constantly being formed at mid-ocean ridges. Because it is basaltic, oceanic crust and associated lithosphere is denser than its continental counterpart, and will subduct away when it gets cold—the oldest oceanic crust is about 180 Ma. As discussed in Grand Challenge 6, the location and source of melting at mid-ocean ridges and oceanic islands is still a matter of debate. Oceanic lithosphere from 0 – 120 Ma seems to be primarily formed by melting plus conductive cooling as the plates move away from the hot mid-ocean ridges, but lithosphere older than this age is thinner than a conductive cooling model would predict. It is generally

Figure 1. An example of Proterozoic lithospheric sutures that have persisted into the present. The right-most portion of the figure shows lithospheric fabric from the active source SNORCLE experiment (Cook et al., 1998; Fernandez-Viejo and Clowes, 2003), and the left part of the figure shows these sutures extend under the ~2.7Ga Slave craton, based on passive source seismology.
hypothesized that small-scale convection plays a major role in this phenomenon, but the exact nature of this convection is still uncertain.

A distinct low velocity zone occurs beneath the ocean lithosphere. This is associated with a low viscosity region, the asthenosphere, where plate motion is mostly decoupled from the deep interior circulation of the Earth. The cause of the low velocities is a matter of ongoing investigation, and it seems to be caused by some combination of temperature, melting, hydration, and grain size. Beneath continents, low velocities are often found, but they have more complex structure than that associated with oceanic asthenosphere. At the asthenosphere-lithosphere interface distinct velocity jumps are found (see Figure 2) and these are now being used to map out continental lithospheric thickness variations. However, these velocity jumps seem to be too large to be due to the thermal or compositional boundary between convecting asthenosphere and passive lithosphere mantle. It may be that the lithosphere-asthenosphere boundary is not simply a passive feature, and may involve small-scale convection associated with the motion of lithospheric “keels”.

Figure 2. An example of the seismic velocity jump associated with the lithosphere-asthenosphere boundary under New England. As shown by the red text, the S-wave velocity jump 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 (Rychert et al., 2007).
Lithospheric seismology is being revolutionized by large scale deployment such as the USArray component of Earthscope, and new techniques such as S receiver functions and “noise” tomography (see sidebars), but many challenges to understanding the evolution and structure of the Earth's lithosphere and lithosphere asthenosphere boundary remain. Some of these are:

- What is the nature of cratons: how did they form, what is their composition, why did they stabilize, and how stable are they over time? Can we image cratons and compositional variations within them seismically? Understanding this will be fundamental to understanding plate tectonics within the early Earth, as well as whether cratonic crust is destroyed over time.
- How do preexisting structures such as ancient faults or sutures affect modern day deformation?
- What aspects of melting, grain scale processes, and rock scale processes cause velocity anisotropy, and how can we use this to deduce the flow and strain state of the lithosphere and asthenosphere?
- What exactly is the asthenosphere: why is it weak, and why is it low velocity? What is the lithosphere-asthenosphere boundary?
- Where and when does small-scale convection and lithospheric delamination occur? Can we use seismically imaged features to deduce how the crust evolved? Where does convection occur in the oceans 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 over time? How deep do boundaries associated with accreted terrains extend?
- How is lithosphere rejuvenated? Are there pyroxenite veins or “plums” of eclogite throughout it and the asthenosphere?

The lithosphere records the history of the Earth from Archean times: understanding its structure will lead to new clues as to its history, and the evolution of the Earth in general. Structure we can see in the crust, as well as the few samples of the mantle we can
observe, suggest there is heterogeneity from the micron-scale to the plate scale. S-wave velocities vary by as much as 13% at lithospheric depths, yet we still struggle to definitively understand the causes of velocity variations. Among the things we will need to unlock this puzzle are: dense seismic arrays throughout the whole Earth including the oceans, high-end computation to analyze the whole seismic waveform, better and cheaper seismometers, open access to the terabytes and petabytes of seismic data to be collected, and close collaboration with geoscientists over a range of disciplines.

References


Backup figures I thought about using
Sidebar: Intraplate earthquakes

Seismologists face a major challenge in estimating earthquake hazards for areas within continental plate interiors, like the NewMadrid and Charleston seismic zones, for two basic reasons. First, we lack a model that gives insight into the causes, nature, and rate of the earthquakes. Second, because intraplate earthquakes are rare owing to the slow deformation rate, we know little about these earthquakes and their effects. However, a combination of recent data are leading to new insights.

Geological and paleoseismic observations indicatethat many continental intraplate faults have episodic seismicity separated by quiescent periods, so the seismicity migrates between faultsystems (Crone et al. 2003). In fact, it seems likely that we are seeing this at New Madrid. GPS geodetic data in the New Madrid zoneshow little or none of the expected interseismic motion expected before a future large earthquake (Newman et al. 1999, Calais et al., 2006). This observation favors models in which the large earthquakes of the past two thousand years such as those that occurred in 1811 and 1812 are part of a temporal cluster (Holbrook et al. 2006) that may be ending. In this model, the present
small earthquakes are aftershocks of the large earthquakes of 1811-1812, and the locus of large earthquakes may migrate. If geodetic data continue to show essentially no motion over longer spans of observations, the idea of the cluster ending will seem increasingly plausible.

This possibility bears out the point that understanding the fundamental earthquake physics is crucial in estimating the earthquake hazard for intraplate areas. This process involves estimating how likely a large earthquake is to occur in a given future time period and what ground shaking would result. Various assumptions yield different results. For example, traditionally it has been assumed such that a future earthquake is time independent - equally probable immediately after the past one and 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 are "early" in their cycles. Moreover, if the New Madrid cluster is ending, the earthquake hazard in the New Madrid zone would be much lower than either model predicts.


continental-interior fault: Holocene Mississippi River floodplain deposits, Madrid seismic zone, USA, Tectonophysics 420, 431-454.


Figure 1: Schematic illustration of alternative models for continental intraplate seismicity. (McKenna et al., 2007)
Figure 2: Comparison of hazard maps for the South Carolina area. Colors show peak ground acceleration 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. (Hebden and Stein, 2008)
Grand Challenge 8. **Dynamical Systems at Plate Boundaries.**

The Earth’s outer layer is continually deforming at the boundaries of tectonic plates. The majority of earthquakes and volcanoes occur in these regions and are the violent response of the Earth to plate boundary stresses. Mountain belts are pushed up, and old oceanic crust is pulled down into the Earth’s interior. New plate is continually formed through the volcanic processes at mid-ocean ridges compensating for plate destruction elsewhere. Not all boundaries create or destroy plate. Along the San Andreas and North Anatolian Fault Systems in California and Turkey the plates slide laterally past one another, sometimes smoothly and sometimes in large jolting earthquakes.

Plate tectonics explains why and how deformation is focused on the boundaries, but as a kinematic theory, it doesn't help us explain what happens as we move away from the plate-bounding fault. A grand challenge is to quantify and then explain the deformation, exhibited as earthquakes, slow slip and creep, that takes place on the network of faults that extend away from the main boundary faults. These broad regions of deformation occur on the continents as well as beneath the oceans as shown in Figure 1.

Current research opportunities exist to harness modern geophysical networks to understand the dynamics of these broad plate boundary systems. Seismic instrumentation provides data for earthquake locations and fault plane orientations, detection of low amplitude tremors, and imaging of plate structure. Geodetic instrumentation maps the accumulation and release of strain, at a variety of strain rates, across the boundary providing a record of deformation that constrains plate rheology. The density of our observations now allows us to ask what role geology plays in driving the development of boundary faults, deformation and seismicity. Can compositional, and therefore rheology, explain how boundaries develop over long time-scales, and do they explain the distribution of seismic versus aseismic deformation at short time-scales?

Earthscope has provided an unparalleled opportunity to study plate boundary systems using integrated geophysical observations and analyses. For example, fundamental
questions about the nature of subduction beneath the Pacific Northwest are only now beginning to be addressed. Until recently we could find no evidence for the subducting Juan de Fuca plate at depths greater than 100km beneath Oregon and Washington despite the fact that subduction has been going on for more that 150Ma. There is an absence of seismicity at depths greater than 100km, unusual for a subduction zone, and efforts to image the slab at depth were inconclusive. Using USArray the fate of the Juan de Fuca plate is now immersing as shown in Figure 2.

Tomographic imaging using the even and dense distribution of seismometers across the western U.S. shows the slab extending through the upper mantle. In the transition zone the high-velocity (blue) down going plate is in conflict with a low-velocity (orange), and therefore buoyant, upwelling anomaly that reaches the surface beneath the Yellowstone Caldera. The interpretation is that the Yellowstone plume broke through the subducting slab on it’s way to the surface. High resolution imaging of this type provides constraints on the interaction of geological objects, a slab and plume in this case, providing information on buoyancy and strength of deep Earth materials. These observations motivate geodynamical models that constrain the dynamics of the plate boundary system.

Segmentation of the Cascadia subduction zone is observed in many forms including the geologic units, composition of erupting lavas, locations of shallow seismicity and characteristics of seismic tremor and slow slip events. Integrating the Plate Boundary Observatory and USArray components of Earthscope, this segmentation is now more clearly defined and appears to be linked. The central segment of Cascadia, with no seismicity deeper than the continental crust, is aligned with the segment with the longest intervals between slow slip and tremor events. This is also the segment with the lowest amplitude seismic velocity of the subducting slab, suggesting it is the warmest segment of the slab, and the lavas from this segment are the driest. The correlation suggests that these processes are linked providing the motivation to develop integrated models for the subduction factory linking deep slab properties with shallow slow slip events, and seismicity with lava composition.
Following the western North America plate boundary south brings us to the San Andreas Fault System. This transform plate boundary has received detail study at the surface. With new observational systems we are beginning to map the deeper structure in detail, allowing us to understand how the pattern of crustal deformation is related to the structure, composition and physical properties of the lithosphere and mantle beneath. To what extent is mantle flow in the asthenosphere coupled to lithospheric processes? Is the deformation at the surface driven by crustal properties or by forces transmitted to the surface through the lithosphere?

Further south still, the plate boundary goes offshore and we reach the third type of plate boundary, a mid-ocean ridge. The East Pacific Rise is one of the fastest spreading centers where new oceanic plate is being generated at a rate of more than 10 cm per year. 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 as shown in figure 3. The crustal formation process therefore cycles large volumes of the mantle through the melting zone generating a compositional heterogeneity between the crust and residual lithosphere beneath. The melt pathways generated by this process remain enigmatic, largely due to the limited data and instrumentation available for study of seafloor processes.

One common observation at all plate boundaries is the role of small-scale structure and processes. In regions with dense geophysical instrumentation we can now quantify the distribution of deformation and image the structural units. By understanding the forces, the structure and the rheology we could build dynamic models of the plate boundary machine.
**Additional figure idea:** Map of the plate boundary from Vancouver Island down to the East Pacific Rise. Topo/bathymetry fig plate boundary locations and types, earthquakes and volcanoes. Could be a vertical runner bar down the side of the page.

Figure 1. Comparison of the idealized rigid plate boundaries and the broad regions currently undergoing diffuse deformation (red) as implied by seismicity, topography and other evidence of faulting. The precise nature of these zone is under investigation.

Figure 2. Tomographic velocity models of the upper 1000km of the Earth beneath the western U.S. 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.
Source: Richard Allen.

Note: probably only want to use right-hand figure. I had this figure so just included the whole thing for now - RMA
Figure 3. 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 to generate the 7km of oceanic crust. Source: UNKNOWN – ask Don Forsyth for a version of this fig that can be included in the report.

Sidebar: Field Laboratories

There are two major experiments underway to drill into active fault zones. SAFOD (San Andreas Fault Observatory at Depth) is drilling into the strike-slip fault that is the plate boundary between the Pacific and North American plates. Part of the EarthScope project, it is located on a section of the San Andreas fault near Parkfield, CA, where there have been repeated magnitude 6 earthquakes over the past 150 years. The Nantroseize experiment is drilling into the interface between the subducting Philippine Sea plate and the overriding continental plate along the Japanese margin. This area along the Nankai trough has been the site of historical magnitude 8 megathrust earthquakes. Nantroseize is an international experiment; the American component is part of the MARGINS initiative and the International Ocean Drilling Program (IODP). Drilling deep into active fault zones is challenging; both experiments will require a decade or more of effort to bring to completion.

One of the primary goals of both experiments is to understand what properties of the faults control the transition between sections that slip aseismically and sections that slip primarily in earthquakes. Both areas have been the sites of extensive subsurface mapping and monitoring using a variety of seismological and non-seismological techniques. Rock samples from the drill holes are being carefully studied and instruments are being installed down hole to study rock properties and to monitor deformation and any small earthquakes that occur on or in the vicinity of the major faults. The descriptions of the experiments below are taken from the EarthScope and IODP websites.
The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a complex ocean drilling project that will be conducted over several years with multiple expedition teams of scientists from all around the world. NanTroSEIZE attempts for the first time to drill, sample, and instrument the earthquake-causing, or seismogenic portion of Earth’s crust, where violent, large-scale earthquakes have occurred repeatedly throughout history.

The Nankai Trough is located beneath the ocean off the southwest coast of Japan. It is one of the most active earthquake zones on the planet. The plan for NanTroSEIZE includes drilling, below the ocean, very deep into the Earth to observe earthquake mechanisms. Samples will be collected in order to study the frictional properties of the rock and sensors are to be installed deep beneath the sea floor to record earthquakes up close. The sensors and sample data are expected to yield insight into the processes responsible for earthquakes and tsunami. The data may shed light on how water and rock interact in subduction zones to influence earthquake occurrence.
Schematic cross section of the San Andreas Fault Zone at Parkfield, showing the drill hole for the San Andreas Fault Observatory at Depth (SAFOD) and the pilot hole drilled in 2002. Red dots in drill holes show sites of monitoring instruments. White dots represent area of persistent minor seismicity at depths of 2.5 to more than 10 km. The colors in the subsurface show electrical resistivity of the rocks as determined from surface surveys; the lowest-resistivity rocks (red) above the area of minor earthquakes may represent a fluid-rich zone.

The Parkfield region is the most comprehensively instrumented section of a fault anywhere in the world, and has been the focus of intensive study for the past two decades. Through sampling, down-hole measurements and long-term monitoring directly within the San Andreas fault zone at seismogenic depths, we will learn the composition of fault zone materials and determine the constitutive laws that govern their behavior; measure the stresses that initiate earthquakes and control their propagation; test hypotheses on the roles of high pore fluid pressure and chemical reactions in controlling fault strength and earthquake recurrence; and observe the strain and radiated wave fields in the near field of microearthquakes.
The SAFOD pilot hole is a separate, 2.2-km-deep scientific drilling experiment carried out near the main SAFOD hole. This site is ~ 1.8 km SW of the San Andreas fault near Parkfield, CA, on a segment of the fault that moves through a combination of aseismic creep and repeating microearthquakes. It lies just north of the rupture zone of the 1966, magnitude 6 Parkfield earthquake, the most recent in a series of events that have ruptured the fault six times since 1857. The Parkfield region is the most comprehensively instrumented section of a fault anywhere in the world, and has been the focus of intensive study for the past two decades as part of the Parkfield Earthquake Experiment. The pilot hole is a collaborative effort between the International Continental Drilling Program (ICDP), NSF and the U.S. Geological Survey (USGS).

Sidebar: Deep earthquakes (Wiens?)
Grand Challenge 9. **Thermo-chemical structures and dynamics of the mantle and core.**

The large-scale 3-dimensional structure of the deep mantle is now quite well-known and is characterized by two very large slow velocity regions (one under Africa and the other under the central Pacific) surrounded by faster material. As shown in Fig. 1, the faster material appears to be geographically related to the subduction zones in the upper mantle though continuity of fast tabular structures throughout the lower mantle is rare. This observation lends support to the idea of intermittent mass transfer between the upper and lower mantle.

The large low velocity structures – usually (but probably inaccurately) referred to as “superplumes” – are remarkable in many ways. While they are slow features in both compressional and shear velocity, the relative behavior of shear to compressional velocity is quite anomalous with much larger shear anomalies than would be expected. This observation is inconsistent with the “superplumes” being caused solely by lateral variations in temperature inside the Earth and we must appeal to other causes such as chemical and/or phase heterogeneity. This conclusion is also consistent with remarkable observations of very strong lateral changes in heterogeneity at the edges of the superplumes which, again, could not be generated solely by thermal effects. There is also increasingly strong seismic evidence that at least parts of the superplumes are denser than their surroundings which is completely contrary to the usual notions of plumes as the locations of light material rising from a bottom thermal boundary layer.

While the above observations are clearly inconsistent with the idea of a simple homogeneous, thermally convecting planet, what has been missing in developing quantitative ideas of how the deep Earth works are observations of the physical and chemical properties of the likely constituents of the lower mantle. This is the realm of mineral physics, which has seen enormous advances in the past few years allowing both theoretical and experimental estimates of material properties at deep Earth conditions. As a consequence, we now know that there is at least one phase transformation that can
occur in mantle minerals at conditions close to that of the core-mantle boundary. The phase boundary of this perovskite—post-perovskite transformations is a strong function of temperature and composition and its discovery has led to a complete re-evaluation of our understanding of the lowermost mantle. What seems clear is that some of the anomalous signals associated with superplumes extend above the depth range where we expect post-perovskite to be able to exist. We therefore are led to the conclusion that at least part of what we observe is due to compositional variations. Enrichment of lower mantle minerals in iron would likely have the effect of increasing density and lowering shear velocity and so is a possible contender for explaining some of the properties of the “superplume” regions. These might more accurately be thought of as chemically distinct piles which could possibly be a reservoir for geochemical tracers that appear to be 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.

More detailed seismological studies of parts of the lowermost mantle have revealed an enormous variety of fascinating structures including regions with extremely low seismic velocities a few tens of kilometers thick situated right at the core mantle boundary (perhaps clustered close to the edge of superplume regions). Variations in fast shear wave polarization directions are consistent with strong lateral gradients in flow direction in this region, and new data-processing techniques have led to detailed imaging of reflectors near the core mantle boundary. These latter observations have recently been interpreted using new observations from mineral physics on the post-perovskite transformation to infer the heat flow from the core! (see side bar). While the velocity signature of the superplumes is clearly present high above the D” region, seismic tomography so far cannot distinguish the fine structure, and in particular determine whether the superplumes are wide upwellings or are made up of a bunch of narrow plumes, or else that the wide piles have a roof at some height above the CMB, in which are rooted narrow plumes. This lack of resolution is due to a combination of available sampling by seismic waves, and theoretical wave propagation tools.
In summary, this brief narrative should demonstrate that our understanding of the deep Earth depends on advances not just in seismology, but in mineral physics, geodynamics, and geochemistry. Much improvement can be made in seismology using the vast new data sets currently being collected (USArray) and new advances in theoretical and computational seismology. Improved imaging of velocity structure at every scale is essential but also are the much harder tasks of developing global anisotropy and attenuation models. Advances in mineral physics might also necessitate a re-thinking of our most basic understanding of the deep Earth. The most recent exotic discovery is the occurrence of a spin transition in mantle minerals containing ferric and ferrous iron. It has recently been demonstrated that the spin transition in ferropericlase (which probably constitutes about 20 percent of the lower mantle) has a strong effect on elasticity at low temperatures. What is not clear is if this effect will persist at high temperatures but, if it does, our understanding of the chemical and thermal structure of the lower mantle will have to be completely re-worked.
Sidebar: Planetary Seismology

Seismology taught us what our planet is made of. Seismology will do the same for other terrestrial bodies – planets and moons – in our solar system. An extremely limited amount of seismic data obtained from our Moon during the Apollo program revealed tremendous amounts of information about the Moon’s internal structure and tidal stresses. Temporary deployments of seismometers on other planetary bodies will be able to answer or address many current significant questions such as the possible presence 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. Planetary seismology will also give us profound opportunities to learn more about Earth by providing other examples of planetary evolution that we can compare Earth to.

The Moon. Seismograms will look dramatically different on different planets and moons than they do on Earth, providing the best means of determining unique differences in temperature, composition, structure and dynamics. For example, lunar seismograms look nothing like seismograms on Earth (Figure x.1.top), but still provided the global structure of the interior of the Moon (Figure x.1.bottom). Apollo lunar seismograms mapped the thickness of a surface regolith layer, responsible for the strong scattering seen in Figure x.1, and identified a low-velocity zone near a depth of 400 km that may be analogous to the more-plastic asthenosphere on Earth. Lunar seismograms also revealed an attenuating region or “shadow zone” for shear waves in the Moon’s deep interior that suggests the existence of a partially-molten core, though one that is primarily silicate rock (as opposed to Earth’s primarily-iron core).

A return to the Moon would provide opportunities to further explore many interesting questions with a new program of lunar seismology

1. Does the Moon’s internal structure and composition support impact hypotheses of lunar formation where the Moon formed largely from the ejecta of Earth’s mantle?
2. What is nature of the mantle/core boundary within the Moon and what is its connection with deep moonquakes?

3. What is the physical mechanism that controls the correlation (Figure x.2) between moonquakes and tidal stresses excited by Earth’s gravitational field?

4. Are the mechanisms of failure for the deep lunar quakes similar to the mechanisms responsible for deep earthquakes that occur within subducted slabs on Earth? Are these related to solid phase changes in silicate minerals?

5. How large are lateral heterogeneities in composition and structure, determined using 3-D tomographic, and what can it tell us about the thermal evolution of the Moon?

**Mars.** A lot of attention is being paid to Mars as the most likely future site of an extraterrestrial human colony, but such plans partially hinge upon the availability of water. The significant effects of water on seismic wave propagation will be able to help resolve this issue. For example, the significant difference in the two seismograms in Figure x.1.top is partly due to the lack of water in the Moon’s regolith and the highly attenuating effects of water within Earth’s surface layers.

While the future of planetary seismology depends upon engineering challenges of designing and building rugged seismometers that can be protected from extreme temperatures, winds, and cosmic radiation, Mars is the most likely planet to be investigated seismically. Mars is likely to be relatively lacking in natural quakes, but mapping the Martian crust and lithosphere will be feasible not only with artificial impacts but also with new techniques of analyzing correlated noise excited by the strong winds of the Martian atmosphere. In addition to the major question of constraining Mars’ possible water cycle, significant scientific problems include understanding the origin of paleomagnetic anomalies that are observed over portions of the surface of Mars.

**Venus.** The planets Venus and Earth are nearly identical in size and bulk density, yet they seem to be entirely different in terms of tectonic history and activity, magnetic field generation, lithospheric structure and atmosphere. Why is this? Venus’ extreme surface
temperatures will make Venusian seismology a greater challenge than for Mars or the Moon, but will be vitally important for understanding the profound differences between these sister planets.

If the lack of a strong magnetic field is related to the lack of a solidifying inner core in Venus, is this because Venus’s core is completely solid or completely liquid? Does Venus undergo whole-mantle convection even if it doesn’t have plate tectonics? If water is scarce in the interior of Venus, does the planet have a low-velocity “asthenospheric” zone like those seen within Earth and the Moon? Seismology can help answer these questions, and these answers will help us understand Earth’s interior as well. For example, water content affects melting temperature and is responsible for lower viscosities and therefore the ease of convection within Earth. Understanding the structure of Venus (and particularly its thick lithosphere) will help us understand the role of water in Earth’s mantle.

**Icy Satellites.** There is a lot of attention now being given to planetary bodies like Europa and Ganymede, two moons of Jupiter, because of the possibility of them having salt-water oceans. On Earth, wherever there is liquid water there is life. Does the same hold for other planets and moons? The first step is to verify the existence of internal salt-water oceans beneath the icy crusts, and this is easily done using seismology because of the inability of S waves to travel through liquids.

**The Sun.** An exciting application of extraterrestrial seismology has been in the development of helioseismology (Figure x.3), which extends seismology from using mechanical oscillators to using satellite-based instruments that detect seismic and acoustic vibrations from the Doppler shifts of the electromagnetic spectra of planetary and stellar atmospheres. This opens up an entirely new field of study that allows the exploration of the Sun’s interior and the nature of its interior convective processes. There are applications to Earth as well. Oscillations in the F layer of Earth’s ionosphere (Figure x.4) (reference) have been shown to couple into acoustic waves in the lower atmosphere and elastic waves in its crust and lithosphere. This coupling may make it possible to
remotely seismically explore the interiors of planetary bodies that either lack solid surfaces (like the gas giants) or have surface environments that are too harsh to allow the deployment of conventional seismometers.

Figure x.1.top seismograms on moon and Earth
Figure x.1.bottom seismic velocity cross section of the moon
Figure x.2 location of deep moonquakes and/or correlation with tidal stresses
Figure x.3 helioseismology – mode patterns
Figure x.4 ionosphere oscillations/figure from Artru… Long…?
Grand Challenge 10. **Earth’s Internal Boundary Layer Processes.**

The emergence of a global distribution of seismograph stations quickly led to the discovery the crust-mantle, outer-core, and inner core boundaries from observations of the reflected and refracted P and S waves. Seismology allowed these boundaries to be located accurately to within several kilometers or less. Expansion of networks and advances in computation and modeling has led to the discovery of new boundaries in composition and phase in the mantle and the inner core (inner core sidebar). Physical properties at these boundaries determined from modeled seismic waves provide images of the temperature and composition of the deep Earth. These images will be important for understanding Earth’s early evolution from gravitative accretion and differentiation and its future evolution driven by cooling and radiogenic heating. The forefront of research now lies in mapping the three-dimensional topography and sharpness of Earth’s boundaries.

Three-dimensional variation and sharpness of a boundary are key to understanding whether its existence is due to changes in chemistry, temperature, phase. Recent advances in full waveform imaging in three-dimensions have shown that combined P and S waveform data over broad angles of incidence make it possible to identify whether a reflector is a boundary in composition, solid-state phase, or combination of the two (Figure x.1). Exploiting advances in computational and experimental mineral physics in predicting the phase boundaries of minerals as a function of pressure and temperature, seismology may soon be able to provide an accurate temperature profile of the earth. An example of these advances, is the temperature profile predicted from images of the post-perovskite phase change predicted near the core-mantle boundary. This result has been made possible in a geographically limited region of the core-mantle boundary by a dense configuration of seismic stations and sources in North and South America. 3-D images of this region of the core-mantle boundary has shown it to be unexpectedly complex, its complexity perhaps related to the chemical and thermal perturbations of slab material reaching the core-mantle boundary. The accurate interpretation of this complexity will be aided by equally highly resolved images of geographically separate regions of the
core-mantle boundary made possible by temporary and permanent arrays of stations on both continents and oceans.

Advances in computational seismology and mineral physics have made interpretation of small perturbations in waveshape valuable observed over even sparsely distributed arrays. Figure x.3 shows an example of how such waveform modeling interpretations can be used to infer both the chemistry and phase of upper mantle reflectors. Challenges in these types of waveform interpretations include separating the effects of phase and chemistry, understanding the effects of subduction and convective transport, and measuring spatial resolution. Future extensions of this power in waveform interpretation include combining the interpretation of boundary topography and sharpness with the temperature, composition, and rheologic variations predicted from geodynamic modeling of mantle convection and plate motion.

Accurate modeling of these small waveform perturbations requires an incorporation or a removal of the effects of earthquake and explosion sources. Techniques for retrieving earthquake source representations have existed since the 1970’s. These techniques, however, have not come into routine use primarily because of a lack of coordinated effort or facility for software and algorithm dispersal. Examples of recent efforts in this direction are the software distributed through the IRIS DMC and the efforts of the CIG organization.

In addition to the more nearly radially symmetric boundaries of the earth, which occur over a small depth range and exhibit small topography, recent imaging and waveform studies have identified boundaries having more general orientation, including near vertically oriented regions of strong spatial gradient in P and S velocity. Examples are the near vertically oriented boundaries bounding a broad low velocity zone beneath the African continent (references). Geodynamic models of this structure include a chemical pile of mantle composition dating from the early differentiation of the earth. This model predicts a unique variation of P velocity confined to a narrow region surrounding the
boundary that can be eventually tested from dense recordings of high frequency P waves (Figure x.4 reference).

Boundaries consisting of spatially broad transitions in properties extending of 10’s to 100’s of kilometers remain a especially strong challenge in structural imaging of the deep earth. Examples include the litosphere/asthenosphere boundary, or the zone at which the more rigid plates decouple from a softer, lower viscosity mantle. This diffuse boundary may exhibit changes in elastic anisotropy and may be characterized by strong changes in water content and rheology. Careful examination of the frequency content of S to P converted waves and anisotropic splitting of shear waves arriving at dense seismic arrays may aid in resolving the nature of this diffuse boundary. Another possible diffuse boundary may reside in the mid-mantle between the upper mantle solid-phase transitions and the lower mantle post-perovskite phase transition. This diffuse boundary is predicted by an electron-spin-transition in iron at pressures corresponding to depths of approximately 1200 km. Whether the effects of this spin-transition are detectable as a diffuse vertical transition or as segregated blobs of smaller scale heterogeneity will be important to understanding mantle chemistry and mixing.
x.1 Images of core-mantle boundary (2) and a possible post-perovskite phase transition (1) from Ping et al., 2008.
x.2 Phase diagram of the post-perovskite phase transition and its behavior at the pressure and temperature conditions near the core-mantle boundary from Lay et al., 2006.

x.3 Models of the SH velocity in the upper mantle determined from waveforms (top) and
possible interpretations of its 650 km deep discontinuity by mineral composition and phase changes from Wang et al., 2006.
x.4 Predicted P and S velocity anomalies associated with a chemical pile beneath South Africa from Helmberger et al., 2007.
Since the discovery of the solid inner core of the earth, expanded seismic data has revealed this small region to be as mysterious and rich in unknown properties as a planet within a planet. Models of the earth’s magnetic field suggest the solidification of the solid inner core from the liquid outer core may provide the energy source required to maintain Earth’s magnetic field. Like the crust and mantle, the inner core appears to have variations in elastic properties both in depth and laterally, including multi-scale variations in attenuation and anisotropy. Large scale lateral differences occur both in latitude and longitude, with the eastern hemisphere faster and less attenuating than the western hemisphere. These lateral structural differences roughly correlate with large-scale lateral structural variations at the core-mantle boundary and predicted flow patterns in the liquid outer core (Figure x.1).

Some seismic observations of the inner-core/outer core boundary suggest that large-scale hemispherical differences in structure may persist on the liquid side of the inner core boundary (reference Yu et al). Evidence for travel time variations and lateral heterogeneity has also been suggested in a cylindrical region containing and tangent to the inner core. If either or both of these observations are confirmed in future studies then the hypothesis that the liquid outer core is a low viscosity fluid, vigorously stirred, turbulent, and radially symmetric, will have to be revised. Such a revision would have a profound impact on theories for the operation and evolution of planetary dynamos.

An emerging challenge in understanding inner core structure is to reconcile differential rotation between the solid inner core and solid mantle with correlations between their lateral structure. Evidence of a possible differential rotation of the inner core was obtained from observations of steady changes in the travel time of compressional waves transmitted through the inner core. The signal of this travel time change is small, difficult to measure, and still not completely understood without correcting for effects of laterally varying structures and earthquake locations. It consists of 0.1’s second measured over
10’s of years (Figure x.2). The source of the torques driving either a differential rotation or wobble of the solid inner core within the liquid outer core may be electromagnetic in origin and related to time variations in fluid flow or electromagnetic fields in the outer core. 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. Understanding this process of growth will be critical to understanding the operation of the geodynamo and the secular variation of Earth’s magnetic field, which is responsible for shielding Earth’s life from cosmic radiation.
Figure x.1 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 (Aubert et al., 2008).
Figure x.2 Variations in PKIKP travel time and its interpretation by differentially rotating inner core with intrinsic anisotropy (Song and Richards, 19xx).
Sidebar: CMB heat flow.

It is not often that a new phase transition that is likely to happen in the deep Earth is discovered so the discovery of the perovskite—post-perovskite transformation has had a huge impact on our thinking about deep Earth processes. Such phase transformations are one of the few ways we have of constraining temperatures in the deep Earth. For example, the freezing of iron is used to constrain the temperature at the inner core boundary and the conversion of upper mantle minerals to perovskite at 660km depth inside the Earth can be used in a similar fashion. The steep gradient of the perovskite—post-perovskite transition (as predicted by experiment and ab-initio calculations) means that it is possible for the geotherm in the lower thermal boundary layer at the core-mantle boundary to intersect the transition twice so producing a lens of post-perovskite sandwiched between perovskite (Fig). If this happens, we actually have two estimates of temperature at closely spaced depths at a single point near the core-mantle boundary – thus giving an estimate of the temperature gradient. All we need is an estimate of thermal conductivity to convert this to a heat flow – a direct estimate of the heat flow from core to mantle! At present, conventional estimates of core heat flow vary by at least an order of magnitude – on the high end, core heat flux is significant and can impact the nature of flow in the lower mantle. On the low end, core heat flux is negligible and there is no significant thermal boundary layer at the base of the mantle.

Some recent seismic studies can be interpreted in terms of a “post—perovskite lens” including those using techniques more commonly seen in exploration geophysics but applied to very large datasets of seismograms which sample the lowermost mantle (Fig ). These studies imply that as much as a quarter of the surface heat flux comes from the core though the uncertainties are huge – particularly in the estimation of the thermal conductivity. Generating such quantities of heat inside the core could be problematic and may require the presence of significant radioactive elements inside the core – this has implications for mechanisms of how the core is formed and is contrary to much of the
conventional wisdom in geochemistry. It may come as a surprise to some that seismology may have important things to say about something as basic as the formation of the Earth and the separation of elements between core and mantle.
Key Seismological Practices

1. Monitoring dynamic processes in Earth’s environment.

Geology has historically labored under a serious handicap: you can’t see through rock. Astronomers can look at the stars, and biologists can look into the structure of a cell, but for years you couldn’t tell what was three feet beneath the surface without digging down there. Not any more. Seismologists have demonstrated that even if you can’t see through rock, you can do a good job hearing through it. The networks of seismometers around the globe are like thousands of stethoscopes that continuously “take the pulse” of the earth and monitor all of its motions.

Earthquakes, volcanoes, ocean storms, glacial flows, slipping tectonics plates and many other natural sources are identified, located and understood through the fundamental monitoring of seismology. In addition, an increasing number of human sources like explosions, urban noise and mine collapses are continuously quantified by seismology, which remains the fundamental means of keeping track of what is going on in and on our planet.

The medical analogy is a good one. If a patient is in critical condition, they don’t just come in for an occasional check-up – they remain in an intensive care unit for continuous monitoring of pulse rate, blood pressure, oxygen levels, etc. Similarly, many geologic and anthropogenic issues have now reached critical levels and require our “patient” to be continuously monitored through networks of seismometers. Issues like dwindling natural resources, waste management, risks from natural hazards, nuclear testing, terrorist activities and the effects of climate change are all becoming increasingly critical in the light of the demands of soaring human populations and industrial development and require increased monitoring from seismic sensors.

MONITORING EARTHQUAKES AND OTHER NATURAL HAZARDS
More than 200,000 earthquakes are located each year. With the potential of instantaneously killing hundreds of thousands of people without warning, earthquakes are a significant natural hazard. Continuous seismic monitoring of earthquakes not only gives us the where and when of earthquakes, but also provides the raw information to determine the how and why, and learning of the physics of earthquake rupture is what is currently allowing us to forecast future earthquakes and perhaps, one day, even predict them. Continuous monitoring has allowed the discovery of new kinds of seismic data that may hold the key to future hazard reduction. For instance, a newly-discovered kind of seismic tremor seems to map out the edges of the rupture zones of giant past earthquakes in the Japan trench, potentially identifying the most likely regions of future rupture.

Seismic monitoring of earthquakes deals not only with sources, however, but also with site responses. To minimize earthquake damage to human structures we need to understand the potential magnitude and style of shaking possible at all locations, and this requires the monitoring of ground responses to earthquakes. The difficulty lies in the non-linear ground response to varying seismic sources due to 3D heterogeneities in near-surface structure. This monitoring need is especially true for critical human facilities like nuclear power plants, nuclear waste facilities, waste transport routes and key government laboratories as well as centers of population. For example, the Kashiwazaki-Kariwa nuclear power plant was shut down in 2007, and remains offline, due to a magnitude 6.6 earthquake that caused a transformer fire and liquid/gas leaks. With the recent licensing of new U.S. nuclear power plants, spurred by growing petroleum shortages, seismic monitoring of source and site becomes increasingly critical.

Seismic monitoring also provides the capability for real-time warnings for many natural disasters. In places of very high earthquake risk, constant monitoring activities are directly connected to infrastructures like high-speed trains and gas lines. A tsunami warning system is in place in the Pacific Ocean and is being installed in the Indian and Atlantic Oceans. These systems use global monitoring to rapidly assess the tsunami potential of an earthquake and (EQS, tsunamis, volcanoes) and rely upon the physical
property that tsunamis travel slower than seismic waves. For instance, a large tsunami generated off the coast of Alaska will take XX hours to reach the coast of Washington and Oregon, giving these areas enough time to evacuate heavily populated coastal areas.

While seismic monitoring is used for forecasting seismic hazards and for real-time warnings of tsunamis and earthquakes in certain regions, it provides the ability to predict with increasing accuracy the dangerous eruptions of some volcanoes. The migration of magma toward the surface creates huge numbers of small earthquakes that reveal the location of the magma. Imaging of volcanic areas also shows temporal anomalies (“4D”-imaging) that are the result of fluid migration. Increased seismic monitoring of volcanoes greatly reduces the loss of life from the eruptions of large stratovolcanoes.

MONITORING OTHER NATURAL SOURCES

Seismometers detect natural earth movements of many different kinds, not just earthquakes and volcanic eruptions. Some of these sources are providing new insights into the basic physics of interior processes like ice flow and fault slip. Some of these sources are able to quantify environmental changes over time. Some of these sources turn out to be entirely unexpected. It is like a person going for a medical check-up. You may have one symptom, but monitoring your internal motions may turn up unexpected conditions that you were glad you discovered. Seismology monitors Earth’s movements, whatever their sources, and continues to make new discoveries with them.

Here is a list of some of the “non-traditional” seismic sources that are monitored with seismic networks and are now being investigated. Many of these sources are further investigated later in this document:

- **Seismic noise.** The microseismic band of “noise” that is ubiquitous on broadband seismograms comes largely from shoreline ocean-land interactions. This and other forms of seismic noise is now being used in a variety of seismic imaging methods. The biggest obstacle to high-resolution imaging of the crust is the high cost of
active sources, but seismic noise is providing a cost-free source for many applications.

- **Seismic noise from ocean storms.** Microseismic noise increases during times of increased storm activity. The long-term monitoring of seismic noise demonstrates a correlation between increased storm activity and increases in global temperatures.

- **Seismic tremor in subduction zones.** Tremor occurs frequently and regularly down-dip of mega-thrust fault regions. This may be increasing stress on the locked fault zone, outlining the transition of slip style and identifying the locations of future large ruptures.

- **Microseismicity at ocean ridge hydrothermal systems.** Mid-ocean ridge ecosystems are unique and of added interest because of their important in understanding the origin of life. It was previously thought that hydrothermal recharge came from off-ridge locations, but patterns of microseismicity now suggest that recharge for thermal vents occurs from downwellings at other locations along the ridge.

- **Glacial processes.** A variety of seismic sources are associated with glacial processes including ice stream flow, iceberg calving, sub-sheet melt-water transport and tidally-generated seafloor slip of ice sheets. These seismic sources are providing insights into the physics of ice stream flow mechanisms and have the potential to be used as proxies for glacier discharge.

- **Mass wasting events.** Downslope movements like rock falls, landslides and lahars release energy that is quantified seismically.

- **Bolide impacts.** The impacts of meteoroids can be quantified seismically. The atmospheric paths are detected through infrasound.

- **Animal migrations.** Whale movements are tracked by monitoring their vocal sounds. Herds of large mammals are tracked seismically.

- **New sources?.** With continuous monitoring of Earth’s motions, new sources are continuously being discovered. It is important not to discount the fact that many exciting seismic discoveries were initially made serendipitously, and many future discoveries will come unexpectedly from continuous monitoring.
MONITORING EXPLOSIONS AND OTHER HUMAN SOURCES

An integral part of seismic monitoring is focused on the testing of nuclear weapons. Since nuclear testing moved underground in the early 1960’s, seismic monitoring has provided political stability by locating and identifying underground nuclear tests. The Comprehensive Nuclear Test Ban Treaty, adopted by the United Nations in 1996, is verified by intensive monitoring of all seismic sources. The rogue test of a nuclear device by North Korea in 2006 was accurately located and its size determined through monitoring by seismic arrays like USArray. As other countries like Iran become nuclear threats, seismic monitoring will be critical for identifying any nuclear activities.

There are many other anthropogenic explosions or implosions that are seismically monitored. Routine mining activity is monitored. Terrorist explosions (2007 Nairobi blast, Oklahoma City Bombing, World Trade Tower explosions) are quantified using seismic analysis. Accidental explosions (factories, gas lines, munitions) are monitored with seismic waves. In many cases seismology plays a forensic role that has no substitute. For example, the implosion of the Russian Kursk submarine was determined seismically. Seismic analysis also showed that the Crandall mining accident was due to a collapse and not an earthquake, as was initially advocated. Seismic monitoring also plays a vital role in military operations. Troop and tank movements are detected seismically through locally deployed seismic sensors. Bomb damage can be assessed seismically. Activities at key facilities and borders, such as tunneling, can be monitored by the high-frequency vibrations they make.

Seismic monitoring is now able to keep track of all kinds of anthropogenic sources, including highway traffic, building construction, dam-induced seismicity, plane and rocket activity, shuttle landings, submarines and ships, concerts, hydrofracturing from underground fluid injection, and any other large cultural noise. Advanced array-analysis methods and techniques for processing noise can now extract significant information.
from the wide array of cultural seismic sources. This continuous monitoring poses tremendous potential for managing human activities.

**MONITORING AND MANAGING NATURAL RESOURCES**

Seismology has always played a primary role in resource exploration, particularly petroleum sources, but also mineral resources, coal, water and soil thickness. Seismic exploration will also play a role in the development of exploration for methane clathrates. These investigations are primarily done with active-source seismology, but there is also an important role for seismic monitoring in the area of natural resource exploration, development and use.

Any time that fluids or gases are added to or removed from the ground there are subsurface changes that can be monitored seismically. These changes can be directly related to hydrocracking or hydrofracturing from fluid migration, or can be the result of changes in the seismic characteristics of reservoirs that can be seen in changing tomographic or migration imaging. Real-time monitoring of underground reservoirs is rapidly becoming one of the most important and societally-relevant areas of geophysics. Modern 4D reflection techniques can detect changes on of the order of 1 meter at a depth of 1 kilometer, and this not only monitors actual reservoirs but provides the means of verifying time-dependent models of reservoir systems.

For example, as petroleum is extracted from a reservoir, monitoring can detect where the resources are being drawn from and show the resulting changes to the entire reservoir. Hazards from extraction can be assessed in real-time. The opposite case also holds true: if waste water is pumped down into a reservoir, seismic monitoring can show where the fluids are going, whether they are remaining contained, and thus allowing a way to determine the useful life of the reservoir. Similarly, the cycling of water through a groundwater system for the generation of geothermal energy can also be monitored to assess levels of efficiency.
One of the most important areas of reservoir use is already in the area of carbon sequestration. Since 1996, when Statiol began injecting CO$_2$ into the world’s first large-scale carbon sequestration field (Sleipner field), underground reservoirs have been important for reducing greenhouse gas emissions, and this need will increase considerably over time. Monitoring these reservoirs by direct sampling has obvious deleterious results, but seismic monitoring shows the distribution of the CO$_2$ over time in an inexpensive and non-invasive manner.

Even as energy sources for power plants move away from the burning of fossil fuels, seismology will be vital for monitoring geologic “batteries” for storing energy. Whether it is due to the inconsistent supplies of solar power plants or the constant base load of nuclear power plants, there will be substantial needs for storing energy during off-peak demand times. One method involves pumping gas into the ground during off-peak times and letting it flow back up during peak times. Another method involves pumping water uphill into an artificial reservoir at the top of a hill during off-peak times and letting it run turbines as it flows back down during peak times. In both cases, the status of the reservoirs will be monitored seismically. And in mentioning nuclear power, it must be added that nuclear waste repositories like Yucca Mountain will be monitored for seismicity and fluid flow using seismology.

**CHALLENGES TO SEISMIC MONITORING**

Given the extent and diversity of applications for seismic monitoring, it is clear that many challenges lie ahead. There is a significant demand for large numbers of inexpensive and easily deployed sensors. The spatial resolution at depth is a direct function of the spacing of seismometers at the surface, so significantly greater numbers of sensors will be required in order to attain the desired resolution for features like shallow-surface reservoirs.
At the same time that a network of high-sensitivity broadband sensors in quiet low-noise locations must be maintained and strengthened in order to assess seismic hazards on global high-risk faults, there will also be a need to put sensors into urban high-noise areas to monitor cultural activities. Sensors will also have to be portable and able to operate under extreme conditions like glaciers and marine environments.

The ability to extending monitoring into ocean-bottom environments will be an important priority for the future. Most major faults occur at ocean trenches, and tsunamis pose an additional marine hazard. It is also impossible to adequately monitor Earth’s activities when 70% of its surface is off-limits. This will require additional research into the development of reliable and inexpensive OBS instruments.

Seismic monitoring is not the sole job of the United States. Increased communication and collaboration with other countries and their national networks is vital to the success of seismic monitoring. Many countries such as Japan and China are making great strides in the deployment of seismic networks, and coordinated efforts would be beneficial to everyone. At the very least it is vitally important that data from all countries are available to free and open access.

The success of seismic monitoring will also rely upon concurrent developments in the processing and analysis of very large seismic data sets. The continued increase in computational power will help in this, but it is important that advances in theory and numerical algorithms find more efficient ways of interpreting the seismic data. It is also important that a new generation of 3D reference models at different scales is created to allow for the identification of 4D anomalies that may develop over time.

Possible Figures:
X. The “Phenomenology” figure from Bill Walter’s ppt (Rick Aster sent it as a possibility for the Monitoring side bar).
X. The photo montage of seismic sources from the start of Michael Hedlin’s ppt (reducing the nuclear explosion to one panel and including a few images of faults and EQ damage)

X. A basic plot of global seismicity. (We can make it small, but I think that we still need this map. We can use the IRIS Seismic Monitor or any other map.)

X. The map of projected global seismic hazards.

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Sidebar: Seismic Source Monitoring and Discrimination

Much pioneering progress in global seismology has been facilitated, either directly or indirectly, by the critical geopolitical need to monitor nuclear testing. This mission led to the establishment of the first modern global seismographic networks and monitoring programs, most notably the World Wide Standardized Seismographic Network (WWSSN) which operated over 100 stations in dozens of nations by the 1960s. Global monitoring of elastic wave phenomena (seismic, hydroacoustic, and infrasonic) is incorporated today in the operations of the IRIS/USGS Global Seismographic Network (GSN), the United Nations Comprehensive Test Ban Treaty Organization International Monitoring System (IMS), U.S. Department of Defense efforts managed by the Air Force Technical Applications Center (AFTAC) and at a host of government, academic, and private seismic networks worldwide. Data from many of these efforts 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. Monitoring operational and basic research is carried out by a worldwide contingent of seismologists. Within the U.S., this activity is performed principally at universities, by the U.S. Geological Survey, and within or supported by the Departments of Defense and Energy. There is widespread consensus among the seismological community that a worldwide monitoring resources and capabilities are sufficient to meet Comprehensive Test Ban Treaty verification goals.
(a 2007 joint statement to this effect from the American Geophysical Union and the Seismological Society of America can be found at www.seismosoc.org/government/position_statement.html).

The deployment of increasingly large networks employing modern high dynamic range seismographs, coupled with the advent of de facto continuous (as opposed to triggered) data recording, offers new research opportunities in the scientific and forensic analysis of novel seismic sources, usually incorporating multidisciplinary corroborative information. Recent studies have included naturally-occurring oceans, atmosphere, and cryosphere, hydroacoustic, acoustic, or seismic sources, (ref other sections as appropriate here), as well a variety of anthropogenic sources, including military and industrial accidents (e.g., the 2000 explosion responsible for the sinking of the Kursk Russian cruise missile submarine in the Baltic Sea with all hands; a 2000 major pipeline breach and explosion in southeastern New Mexico that killed 12) and acts of terrorism (e.g., the 1995 Oklahoma City bombing; the 1998 U.S. Nairobi embassy bombing; and the 2001 collapses of the World Trade Center). Special efforts of the seismological community presently concentrate on critical earthquake and volcano monitoring, nuclear monitoring, and tsunami warning efforts. However, more general comprehensive scanning of the global infrasound, hydroacoustic, and seismic wave field would produce a new depth of insight into natural and anthropogenic sources of elastic waves.
Schematic view of the monitoring environment. Energetic processes in the atmosphere, solid earth, and hydrosphere (not shown) create seismoacoustic waves that are readily detected with sensor networks, and frequently form a core component of multidisciplinary monitoring efforts. C/o William Walter and David Harris, Lawrence Livermore National Laboratory.

Seismic source discrimination is a critical problem that has been approached through decades of research and development. As network coverage and data quality improve, seismogram inversion techniques become increasingly accurate in facilitating the robust quantitative discrimination of various source processes from remote seismic recordings, for example, between underground collapses, earthquakes, and nuclear and other explosions. Shown are example events mapped according to the relative magnitude of their moment tensor elements estimated from seismogram inversion. The moment tensor characterizes the idealized point source force system responsible for observed seismic radiation and is thus highly diagnostic of differing source processes. The Crandall Canyon mine collapse, which ultimately killed six miners and three rescue workers, had parameters determined from six regional
seismographs (map at right). Three-component seismic modeling fits to the Crandall mine data for all stations shown are shown at lower left. The 2006 North Korean test had an estimated yield of approximately 1 kT (and corresponded in seismic energy to about a magnitude 4.2 earthquake). After Dreger et al., 2008.

2. Multi-scale 3D and 4D imaging of complex Earth systems and synthesizing waves in the resulting models.

Source imaging

In seismic source imaging one uses the polarization and timing of waves to establish the strike and dip of the fault plane on which the earthquake occurred, as well as its origin time, hypocenter, and the direction of slip. Seismic source characterization played a major role in the discovery of plate tectonics, in particular in the establishment of the sense of slip on oceanic transform faults, which provided key evidence for sea floor spreading. In subduction zones, where tectonic plates are consumed by the Earth's mantle, the existence and distribution of deep earthquakes helped establish the nature of this geological process, which is an aspect of the surface expression of the convection of the underlying mantle. By the nineteen eighties, the global seismographic network had enabled the routine analysis and cataloging of earthquake activity, an invaluable effort that continues to this day in the form of the global centroid moment-tensor (CMT) project (globalcmt.org). This project involves near real-time analysis of all global earthquakes of magnitude 5.5 and greater. The CMT catalog currently contains more than 25,000 earthquakes.

Today, seismologists routinely determine finite source models that capture the rupture process during an earthquake. The details of this kinematic rupture process put constraints on the dynamics and the underlying physics of earthquakes. Figure~?? shows an example of kinematic source imaging for the 2004 magnitude 9.2 Sumatra-Andaman earthquake based upon data from the Japanese HiNet seismic array (Ishii et al.).

Should we say something here about ETS?

Structural Imaging

In the last century, seismologists such as Jeffreys, Bullen & Gutenberg established the
basic one-dimensional, spherically symmetric structure of the Earth. This included the
discovery of the metallic core, which is separated from the Earth's silicate mantle by the
core-mantle boundary (CMB), and the subsequent detection of the inner core (see one of
the side bars). The inner core is the result of slow crystalization of the liquid outer core as
the Earth cools, and the nature and location of the inner-core boundary (ICB) provide
constraints on the Earth's thermal history and the dynamics of the outer core, in particular
the generation of the Earth's magnetic field. In the upper mantle, careful analysis of
seismic traveltimes led to the discovery of major discontinuities at depths of 220 km, 410
km, 520 km, and 660 km. The location and nature of these discontinuities puts tight
controls on the underlying mineral physics, thereby providing estimates of the Earth's
composition. The culmination of nearly a century of work was the establishment of the
Preliminary Reference Earth Model (PREM) in 1981. Contrary to earlier spherically
symmetric Earth models, which were largely determined based upon the traveltimes of
compressional and shear seismic body waves, PREM was also constrained by precise
estimates of the resonance periods of the Earth's free oscillations and the dispersion of
Love and Rayleigh surface waves. The establishment of a global seismographic network
comprised of broadband sensors enabled the detection and analysis of this wide spectrum
of seismic signals. The determination of an Earth model that was consistent with all
manner of seismic waves over a very broad range of frequencies, from 1-2 Hz body
waves to surface waves with periods of a few minutes to free oscillations with periods of
almost one hour, led to the incorporation of two important wave phenomena: attenuation
and anisotropy. The effect of attenuation on seismic waves is two fold: 1) it reduces the
amplitude of a wave with time and distance, and 2) it introduces physical dispersion, such
that waves with shorter periods travel faster than waves with longer periods. Fitting
seismic waves over such a broad period range required the introduction of attenuation.
The effect of anisotropy is to impose a directional and polarization dependence on
seismic wave speeds, and this is required to fit both Love and Rayleigh surface waves.
The seismic signatures of attenuation and anisotropy may be used to our advantage,
because they provide powerful constraints on temperature, fluid content, and mineralogy.

With the basic spherically symmetric Earth structure determined in the early nineteen
eighties, seismologists started to turn their attention to resolving lateral variations in seismic wave speeds using broadband data from global seismographic networks. This led to the still-booming field of seismic tomography, the seismological equivalent of a medical CAT scan.

Shallow lateral variations associated with differences between oceanic and continental crust were already recognized by post-war seismologists, but in the early nineteen eighties seismologists used free-oscillation data to reveal a geographical pattern of lateral heterogeneity in the upper mantle transition zone, between 410 km and 660 km, dominated by spherical harmonics of angular degree two. This was soon followed by long-wavelength images of the entire mantle, revealing both compressional- and shear-wave speed variations. Beautiful images of large-scale upwellings underneath Africa and the Pacific established a dominant degree-two pattern of mantle convection in the lower mantle. In recent years seismologists have discovered an anti-correlation between lateral variations in bulk sound speed and shear wave speed in the lower mantle. This observation is evidence for the existence of both thermal and compositional heterogeneity in the mantle (see the section "Thermo-chemical structures of the mantle"). There are also indications from free-oscillation data that lateral variations in density are anti-correlated with lateral variations in shear wave speed, thus providing further evidence for compositional heterogeneity. Surprisingly, the edges of the large-scale upwellings beneath Africa and the Pacific can be very sharp, with 3% variations in compressional wave speed over length scales of less than 50 km.

Spectacular images of subducting tectonic plates led to the discovery that slabs can sometimes get stuck in the transition zone, whereas in other locations they go straight through the 660 km discontinuity in to the lower mantle. These observations have implications for the dynamics of the mantle, and geodynamicists use this in the development of thermo-chemical convection models. From a geochemical perspective, the style of mantle convection implied by the tomographic images restricts the interpretation of trace element abundances and related mantle reservoirs.
Imaging of oceanic crust and upper mantle structured is hampered by a lack of oceanic stations, and there continues to be a pressing need for the deployment of a global ocean bottom seismographic network. In the mean time, seismic surface waves provide a good tool for imaging below the oceans. Surface-wave dispersion measurements have revealed a distinct signature of lithospheric cooling as predicted by the cooling half-space model. They also provide clear and convincing evidence for seismic anisotropy associated with the sea floor spreading direction as preserved in the mineral fabric.

The CMB region provides some of the most baffling observations of seismic wave propagation. Careful analysis of shear waves either reflecting off the CMB or turning just above the CMB has revealed the existence of the so-called D" discontinuity. Recent advances in mineral physics suggest that this discontinuity is related to a post-perovskite phase transition. The CMB region is also home to very thin (< 50 km) ultra-low velocity zones (ULVZs). Whether these ULVZs are associated with partial melt of the lowermost mantle, the result of underplating of the CMB in a sedimentation process due to core differentiation, or a thin mixing zone between the core and the mantle remains open for debate. There are also indications of anisotropy near the CMB, presumably indicative of mantle flow in this region. Lateral variations in composition and temperature in D" have profound implications for the temperature flux across the CMB, and this in turn controls the style of magneto-hydrodynamic convection in the outer core and ultimately the nature of the magnetic field at the Earth's surface.

The inner core is one of the most fascinating parts of the Earth (see side bar). There is a collection of spheroidal modes whose splitting cannot not be explained in terms of the Earth's rotation, ellipticity, and lateral heterogeneity. What these so-called "anomalously split modes" have in common is that they are sensitive to the inner core. Another inner-core related observation is that compressional body waves traveling parallel to the Earth's rotation axis through the inner core arrive faster than waves traveling in the equatorial plane. Both sets of observations may be explained in terms of an anisotropic inner core. This hypothesis has spurred much research in allied fields such as mineral physics and core dynamics. Recent research suggests that the inner core may have a seismically
distinct center, leading to the suggestion of the existence of an "innermost inner core". Numerical models of the geodynamo predict that the inner core can rotate at a slightly different rate than the mantle. Seismic evidence strongly suggests that the inner core may indeed exhibit temporal variations on decadal time scales. Detection of the tiny arrival time fluctuations associated with inner core motions is another testament to the quality of the data recorded by the global seismographic network over the past decades.

The amplitudes of seismic waves contain valuable information about lateral variations in attenuation. Extracting this information is a challenging problem, because many other effects cause amplitude variations, including elastic focusing and defocusing of seismic energy and the earthquake source mechanism. Nevertheless, using strict data selection criteria and carefully accommodating known elastic and source effects, large-scale lateral variations in attenuation have been successfully imaged. Because attenuation is strongly affected by temperature, anelastic tomography helps to image hotter than average regions of the mantle.

A marvelous recent development in seismic tomography involves harnessing what is traditionally considered to be noise in seismograms. In the absence of earthquakes, there is still lots of seismic energy in the Earth generated by ocean waves and atmospheric winds. This "hum" of the Earth can be turned into signal by cross-correlating the noise recorded by two nearby station to reconstruct Rayleigh surface waves traveling between the two stations. By cross-correlating many station pairs, these Rayleigh wave reconstructions may be used to perform traditional surface-wave tomography. This approach has been used extensively in many geographical areas using data from dense regional networks, including the region currently covered by the US Array.

The current trend in seismic tomography is towards "finite-frequency" imaging, in which the band-limited nature of seismic signals is harnessed to probe different aspects of the Earth's structure. This more complete theory of seismic wave propagation takes account of wavefront healing and represents a significant step forward from traditional ray theory, which is rooted in geometrical optics. The first compelling finite-frequency images of
plumes emanating from the CMB were recently published.

In exploration seismology the state-of-the-art is time-lapse or "4D" imaging. This approach involves acquisition, processing and interpretation of repeated seismic surveys over a producing oil field. The goal is to monitor changes in the reservoir due to oil and gas extraction and/or the injection of gas or water by comparing repeated datasets. The differences between datasets highlight the migration of fluids and gases, thus enabling more effective exploitation of the reservoir. Using the same philosophy, in crustal seismology repeated applications of noise cross-correlation tomography in a geographical area of interest can reveal subtle changes in seismic wave speeds, e.g., related to fluid flow or magma migration. This approach was successfully used to highlight reductions in shear-wave speed associated with the inflation of Piton de la Fournaise volcano (include figure).

The establishment of three-dimensional models of the Earth's interior has led to a need for accurate simulations of seismic wave propagation. In the latter part of the past century, one had to resort to asymptotic methods for the calculation of synthetic seismograms. Nowadays, taking advantage of modern numerical algorithms and large parallel computers, seismologists are routinely calculating fully 3D synthetic seismograms in complex 3D Earth models.

The current challenge lies in harnessing these numerical capabilities to enhance the quality of tomographic images of the Earth's interior, in conjunction with improving models of the rupture process during an earthquake. This formidable problem may be solved iteratively by numerically calculating the derivative of a "misfit" function. The construction of this derivative involves the interaction between the wavefield for the current model and a wavefield obtained by using the time-reversed differences between the data and the current synthetics as simultaneous sources. For a given earthquake, only two numerical simulations are required to calculate the gradient of the misfit function: one for the current model and a second "adjoint" simulation for the time-reversed differences between the data and the synthetics. Adjoint methods may be used in
combination with a conjugate gradient method to iteratively reduce the misfit between
data and synthetics, thereby improving source and structural models. There are close
relationships and parallels between adjoint methods, the "imaging principle" widely used
in exploration seismology, finite-frequency tomography, and time-reversal acoustics. In
fact, what is called "imaging" in exploration seismology is really just the first step in an
iterative inversion based upon adjoint methods. For a typical regional or global dataset,
"adjoint tomography" involves thousands of 3D simulations and hundreds of thousands
of CPU hours, i.e., it requires fast and easy access to large parallel computers.

Current tomographic models reveal only large-scale features of the Earth's interior,
features with dimensions much larger than the wavelengths of 1 s waves. To image
smaller scale features, e.g., the detailed structure of mid-oceanic ridges and subduction
zones, ULVZs and anisotropy just above the CMB, and the structure at the top of the
enigmatic inner core, we need to be able to accurately model 3D wave propagation at
these short periods. Currently we can only reach these periods for simple spherically
symmetric Earth models, but the advent of petascale computing will enable these kinds 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.

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Sidebar: Fault healing.

Ambient Noise and Fault Healing

The ground is constantly vibrating, even in the absence of earthquakes. This “ambient
noise” has been studied for years, and a peak in noise energy between wave periods of
roughly 30s and 1s has long been known to be caused by ocean waves. Most
seismologists viewed this microseismic noise band of highly scattered energy as just that-
oise--but after a long period of gestation it was shown that cross-correlating
microseismic noise between two stations gives a close approximation to the surface wave
Green's Function between the two stations. This means any seismometer in an array can
be used as a virtual impulsive source and the other stations will record the surface waves associated with that source. Since natural sources are typically heterogeneous in their distribution, this is an exciting development that has tremendously improved resolution of structure on many scales, especially for large arrays of seismometers. For instance, ambient noise tomography using the USArray seismometer array of 400 broadband instruments is producing unprecedented resolution of lithospheric structure.

Below, another exciting development using ambient noise tomography is shown. In this case, Brenguier et al. have used ambient noise to look at the temporal changes in velocity along the San Andreas Fault, near Parkfield, California. The top part of the plot shows how the along-fault velocity undergoes two reductions, correlated with the San Simeon earthquake that was off the Fault, and the Parkfield earthquake that was on the fault. The increase in along-fault velocity after the earthquakes suggests the faults are healing over time and promises future insight into the earthquake cycle as faults break and heal. The red line that shows a remarkable fit to the data is the GPS displacement along the fault, and the filled in black lower plot is the amount of non-volcanic tremor (low frequency fault energy) occurring every day. That the along-fault velocity, displacement, and non-volcanic tremor all correlate over time suggests stress relaxation in the deeper part of the fault zone.
References


Sidebar: Physics-based prediction of ground motions using realistic fault rupture models and 3D geological structures. (Beroza)
Sustaining a Healthy Future for Seismology

The panoply of seismological research and societal applications overviewed above is the result of past extensive investment by many agencies, industry and universities; sustaining the positive trajectory of Seismology contributions requires strategic investment of future resources. Discussion of the disciplinary needs and recommendations for the future are summarized here.

Key to all undertakings in Seismology is maintaining a steady flux of talented people with solid quantitative skills into university programs, training in fundamentals of seismological theory and practices, and retention of the expertise in academic, industry, national laboratory, regulatory and Federal agency careers. Attracting more students to this exciting and important discipline requires improved visibility of its many societal contributions and exciting research frontiers, along with stable funding for graduate programs that prepare new seismologists for the tasks of tomorrow. The Seismology workforce demands of industry are not being fully met and new partnerships between energy exploration industry and academic programs could be developed to attract undergraduates to the discipline. 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 play an important role in informing society about the importance of the science and how it contributes to society.

RECOMMENDATIONS:

• Seismology community organizations like IRIS, SCEC and the SSA should engage with industry to establish pipelines of undergraduate students to the discipline
• E&O efforts should….  

Analysis of huge seismic data sets, inversion for 3D and 4D multi-scale models of the interior, and robust calculation of broadband seismic ground motions for realistic, non-
linear earthquake and explosion sources presents huge computational challenges. University research on these topics relies on access to both moderate-size in-house computer workstations and clusters and to large-scale computational capabilities of national laboratories and integrated networks of cyberinfrastructure such as the Terragrid. Standardization and dissemination of some advanced seismic software is being undertaken by the Computational Infrastructure for Geodynamics (CIG) initiative of NSF, and further development of these efforts will advance Seismology.

RECOMMENDATIONS:

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With availability of high-quality, widely distributed recordings of ground motion lying at the heart of all seismological research and monitoring activities, strong commitments are needed to sustain continuous, long-term observations at global observatories of the FDSN, the IRIS Global Seismic Network (GSN) and the CTBTO IMS, as well as regional seismic networks operated by the USGS and stations and arrays operated in support of national nuclear monitoring activities. Sustained maintenance and operation of these stations is essential for both national security, global monitoring of the environment, earthquake and tsunami hazard warning and response activities, and investigations of the Seismological Grand Challenges.

RECOMMENDATIONS

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In parallel with fixed observatories, large pools of deployable instruments are essential for seismological investigations of continental and oceanic environments at higher resolution that afforded by permanent stations. The IRIS Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), EarthScope Transportable and Flexible Array instruments, Ocean Bottom Seismometer Instrumentation Pool (OBSIP), and R/V Marcus G. Langseth research vessel are critical facilities to sustain with long-term amortization and investments in new technologies. While improved seismic
instrumentation of the ocean environments will be achieved by the new NSF Ocean
Observatories Initiative (OOI), the current plans have become rather limited, and there is
need for much more extensive coverage of ocean environments using sub-surface
borehole seismometer deployments and an expanded pool of ocean bottom seismometers.
Systematic deployment of OBS instruments in targeted areas of the oceans holds great
promise for scientific break-throughs, as proposed in the Ocean Mantle Dynamics
Science Plan (200x) produced by the NSF-funded community.

RECOMMENDATIONS

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While many seismological studies utilize natural or commercial seismic sources, high-
resolution investigations often require additional sources for research efforts. Sustained
and improved availability of sources such as the vibrator trucks of the Network for
Earthquake Engineering Simulation (NEES), and underground explosive capabilities of
the USGS are required. The continental imaging efforts of the USGS have largely
diminished over time, and there is no longer a dedicated internal program for what had
been a major area of contribution. Permitting and transport of explosive materials is very
difficult for universities and Federal support on this issue is essential to active source
investigations of the near-surface environment.

RECOMMENDATIONS

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Efforts to foster open-access to real-time seismic data from all international data
collection activities need to be made, building on the examples of the USGS NEIC, IRIS
DMC and FDSN-participant data centers, along with many U.S. University programs.
Efforts to make available data that are not now freely available, such as the IMS seismic
recordings and other restricted seismic data sets, will enhance multi-use of the
corresponding signals for investigating important topics in the Earth system.
RECOMMENDATIONS

Progress on the Seismological Grand Challenges listed in this document and the many societal applications of Seismology hinges on improved interdisciplinary interactions and communications. Strong synergisms exist within the Earth Sciences 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 Incorporated Research Institutions for Seismology (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. These efforts need to be sustained, and improved communications and coordination on Seismology activities needs to be fostered between NSF Earth Sciences (EAR), Ocean Sciences (OCE), Atmospheric Sciences (ATM) and Polar Programs (OPP) divisions. Coordination at the GEO directorate level of NSF can help to overcome existing institutional barriers to effective cross-divisional activities of Seismology. 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 Agencies.
Technological advances permeate the discipline of Seismology, which is quick to embrace advances in computer storage and processing, telecommunications, internet dissemination of information, and advances that come from other areas. Specific to the discipline are needs for seismic sensor and high resolution data acquisition advances. 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 the Earth’s free oscillations, slow earthquake motions, and very long period ‘noise’ with high fidelity. New micro-electro mechanical systems (MEMS) are being designed to sense short-period ground vibrations, and further development of this technology should be vigorously pursued to enable vast increases in inexpensive sensors that can provide high density sampling of ground motions in urban and remote areas, with many potential applications. New three-component seismic sensors for hostile environments (extreme cold, ocean-bottom, and deep boreholes) are of great importance for expanding the 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. Partnerships with industry, national laboratories, and Federal agencies must be developed to sustain seismic instrumentation innovation and enhanced capabilities.

RECOMMENDATIONS

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VII. Summary

Seismology is an exciting, vigorous and important discipline, with broad relevance to major challenges confronting society such as environmental change, coping with natural hazards, energy resource development, and national security. Seismology provides the highest resolution probe of inaccessible regions of the Earth’s interior from shallow crustal rocks to the central core, and it thus plays a primary role in efforts to understand the structure and dynamics of Earth’s many interior systems.

Yada yada yada
Recommended Additional Reading


([http://www.agiweb.org/gap/trans08.html](http://www.agiweb.org/gap/trans08.html))


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


List of Acronyms and Titles

AGU – American Geophysical Union
ATM – Atmospheric Sciences Division of the NSF
CIG – Computational Infrastructure for Geodynamics funded by the NSF
CIDER – Cooperative Institute for Deep Earth Research
COMPRES – Consortium for Materials Properties Research in Earth Sciences
CSED1 – 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 research equipment facility for studying North America continent
EERI – Earthquake Engineering Research Institute
FDSN – International Federation of Digital Seismograph Networks, an IASPEI commission with 52 participating countries
FEMA – Federal Emergency Management Agency
GEO – Geosciences Directorate of the NSF
GEOSS – Global Earth Observation System of Systems
GSN – Global Seismic Network
IASPEI – International Association for Seismology and Physics of Earth’s Interior
IMS – International Monitoring System of the CTBTO
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
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
RIDGE – Ocean ridge research program of the NSF
SCCEC – Southern California Earthquake Center
SEG – Society of Exploration Geophysicists
SSA – Seismological Society of America
UNAVCO – University consortium for high-precision measurement of crustal deformation
USGS – United States Geological Survey