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Grand Challenges for Seismology

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Seismology is the study of the propagation of elastic waves, the sources that generate them, and the structures through which they propagate. It also is a fundamental, high-resolution tool for exploring the interior of the Earth from crust to core, as well as other bodies in the solar system. A remarkable diversity of multidisciplinary societal applications of seismology has emerged, including hydrocarbon and resource exploration, earthquake detection and hazard assessment, nuclear test monitoring and treaty verification, volcano and tsunami warning systems, and aquifer characterization. New directions in seismology are evolving that are relevant to climate and environmental change, such as resolving fine-scale seismic stratigraphy, monitoring carbon sequestration, detecting sudden movements of glaciers and ice sheets, mapping the internal fine structure of the ocean, and reconstructing the twentieth-century history of global storm activity from ocean-generated seismic noise.

The broad scope of seismological research positions the discipline to contribute significantly to the U.S. National Science Foundation (NSF) Directorate for Geosciences' emphases on dynamic Earth processes and climate change in the 2010 budget request to Congress.

The seismological community, through a community workshop and writing committee process sponsored by NSF, earlier this year identified 10 grand challenges for seismology at the forefront of research on Earth systems. The resulting document, "Seismological grand challenges in understanding Earth's dynamic systems," was published in early 2009 and is available online at http://www.iris.edu/hq/lrsps. The report is directed at a broad readership, including researchers and educators in other disciplines as well as a general academic and government audience. The report includes a number of sidebars illustrating recent discoveries and applications that are appropriate for classroom and other broad use.

The grand challenges, which are framed by fundamental research issues, encompass mitigating natural hazards, monitoring the environment, discovering and mapping natural resources, contributing to national and international security, and understanding the dynamic processes in the interior of the Earth. This article provides a summary of the 10 grand challenges.

Specific Challenges

How do faults slip? The steady motions of the tectonic plates build up stresses that are relieved mainly through slip on faults. Recent observations have revealed a rich spectrum of fault behavior, ranging from steady sliding with little apparent resistance to earthquakes that can slide at supershear velocities (faster than the speed of *S* waves in the rocks) and that can emit shock waves that may cause exceptionally damaging ground motions. Only in the past decade has it been discovered that major parts of some fault systems slip repeatedly in slow events that occur surprisingly regularly, accompanied by low-amplitude seismic tremor (Figure 1). There are many specific issues remaining to be addressed, such as the relationship of this episodic slip and tremor to major earthquakes, and achieving a detailed physical understanding of the nonlinear processes by which faults slip is a major challenge.

How does the near-surface environment affect natural hazards and resources? The location and severity of many natural hazards are strongly influenced by near-surface material properties. Determining Earth's history of natural climate change relies in part on seismic imaging of shallow sedimentary deposits that record and respond to climate variations. Near-surface processes affect water, energy, and mineral resources at depths of meters to a few kilometers. Detailed knowledge of the Earth's near surface is therefore a crucial part of managing a sustainable environment for civilization. One of the most important challenges for seismology is to understand how strong ground

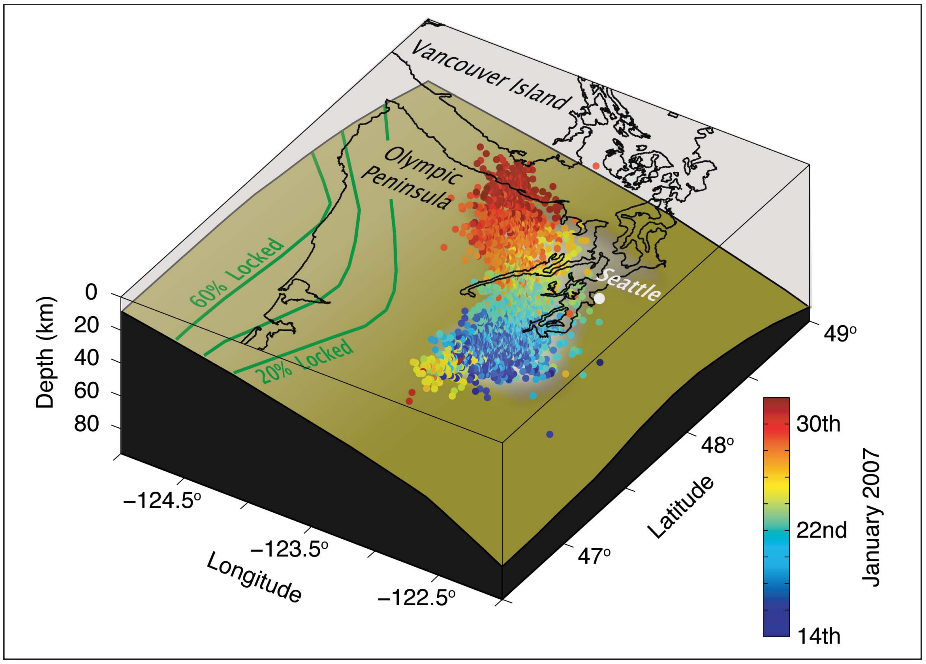

Fig. 1. Location of migrating tremor during a 2- to 3-week episode of slow slip on the Cascadia subduction zone. Most of the relative plate motion in the slow slip area is accommodated by similar slip events that repeat approximately every 14 months. Plate boundary slip in the "locked zone" to the west of the contours of partial locking occurs during great earthquakes such as the M$_w$ *~9 Cascadia megathrust earthquake in 1700. Locking refers to the percentage of slip between plates that occurs in stick-slip events as opposed to gradual, nearly continuous creep. Image courtesy of A. Wech and K. Creager.*

By D. W. Forsyth, T. Lay, R. C. Aster, and B. Romanowicz

motions are produced by earthquakes and to translate this understanding into improved hazard maps. Nonlinear responses to shaking, such as soil liquefaction, and the complex pattern of strong ground motions can be predicted with comprehensive three-dimensional (3-D) modeling of potential earthquakes and knowledge of soil properties, an undertaking that straddles the interface between seismology and earthquake engineering.

What is the relationship between stress and strain in the lithosphere? Plate tectonics provides the kinematic framework for describing rates of deformation, but it does not quantitatively account for how plates move and deform. Rheology describes the linkage between the forces (stresses) and the resulting deformation (strains). Motions and strains now are precisely measured with satellite imaging and networks of Global Positioning System receivers, strainmeters, seismometers, and tiltmeters, but the causative stresses only can be inferred. Meeting the grand challenge of understanding the stress distribution and the temporally and spatially dependent rheology is necessary to unraveling how some earthquakes trigger other earthquakes thousands of kilometers away or how, for instance, the great Sumatra earthquakes of 26 December 2004 (seismic moment magnitude $M_w = 9.3$) and 28 March 2005 ($M_w = 8.7$) were coupled.

How do processes in the ocean and atmosphere interact with the solid Earth? Ocean storms, bolides, tornadoes, and glacier calving all generate signals that are readily detected by seismometers and atmospheric infrasound recorders. The multidisciplinary topic of how processes in the ocean and atmosphere couple into seismic waves and how these waves can be used to monitor the global environment is one of the high-priority challenges. Recently, it was established that the Earth's long-period "hum" of free oscillations continuously excited at periods of hundreds of seconds is generated by midlatitude winter storms through an as yet poorly understood mechanism. On the other end of the seismic frequency scale, active sources used in seismic profiling, such as in routine imaging of subseafloor structure, can detect layering and mixing in the water column itself. The images' unprecedented horizontal resolution can help with understanding internal waves, turbulent mixing, and ocean circulation.

Where are water and hydrocarbons hidden beneath the surface? Seismological techniques have long been used to map aquifers and explore for hydrocarbon resources. Modern exploration seismology methodologies, including 4-D (time lapse) mapping, routinely are used to monitor the extraction and movement of hydrocarbons in real time on land and at sea. Similar approaches now are being applied to investigate the potential for carbon dioxide sequestration, and these approaches will be critical for managing these efforts. Looking deeper, there is great interest at present in deducing where and how much water is stored in the mantle (which may amount to more than five ocean volumes) and whether changes in mineralogical phase lead to greater concentrations of water in the mantle transition zone and cause regions of partial melt near the global 410-kilometer-deep discontinuity.

How do magmas ascend and erupt? Seismological monitoring is one of the primary ways of forecasting or predicting volcanic eruptions. An increase in microearthquake activity and harmonic tremor, or changes in seismic velocity as moving magma changes the shape of the volcano and fractures the surrounding rock, often precedes eruptions by several days, providing some warning of an eruption. Current eruption prediction methods are primarily empirically based, however, because magma plumbing systems are poorly known. A major challenge is to improve scientific understanding and prediction capabilities through better determination of the physical changes that accompany eruptions, including improved imaging of the interior of volcanic systems and quantitative characterization of magma migration and eruption processes.

What is the lithosphere-asthenosphere boundary? The lithosphere is Earth's mechanically strong outer shell that makes up the tectonic plates, underlain by the weak asthenosphere, which flows and deforms to accommodate plate motions. The lithosphere often is thought of as the thermal boundary layer between the cold surface of Earth and the planet's hot interior, but recent studies have shown that there is often a sharp seismic discontinuity at the base of the lithosphere inconsistent with a simple gradual thermal transition. Changes in composition, volatile content, and anisotropy of the mantle, and perhaps the presence of melt, may play roles in creating the discontinuity. Lithosphere-scale seismology is being revolutionized by new data from large-scale seismometer deployments, such as the USArray component of the NSF-funded EarthScope project, and by new analysis techniques. However, many challenges to understanding the evolution and structure of the lithosphere and the asthenosphere remain.

How do plate boundary systems evolve? Most earthquakes and volcanoes occur at plate boundaries. Most of the deformation and volcanic activity at plate boundaries in the oceans may take place in a zone only a few hundred meters across at the surface, yet plate boundary systems may be hundreds of kilometers wide in the continents. The geometry of these diffuse boundaries changes with time, and the areas within the boundary system that are most active may shift. Coordinated seismological, geodetic, geomorphological, deep drilling, and geological studies are needed to meet the challenge of determining what controls the location, width, and activity of dynamically evolving plate boundaries.

How do thermal and compositional variations control convection in the mantle and core? The thermal evolution of the Earth, the driving forces of plate tectonics, and the generation of the magnetic field all involve convective flow in the mantle and core. Improving the seismological resolution of deep structure as data accumulate and as new analysis methods are developed will help reveal the patterns of flow. Recent observational studies, combined with mineral physics experiment and theory, have shown that large-scale chemical heterogeneity is present in the mantle and that the interaction of compositional and thermal buoyancy must be considered in modeling convective processes. The large-scale 3-D elastic structure of the mantle is now fairly well known, but where detailed studies provide higher resolution, pronounced sharp or short-wavelength features are found. This suggests that small-scale convection plays a critical role in the dynamics of Earth's deep interior.

How are Earth's internal boundaries affected by dynamics? Internal boundaries in Earth (and other planets) are associated with the primary compositional layering that resulted from the chemical differentiation of the planet and with mineralogical phase changes controlled by pressure and temperature variations. These boundaries may be deflected by convective processes, thus providing clues to the location and intensity of upwelling and downwelling. Because changes in rheology, composition, and density occur across the boundaries, they can in turn exert a strong influence on the pattern of convection. The challenge for seismology is to map these boundaries, including their 3-D topography and sharpness, which are key clues to quantifying their mineralogical, thermal, and compositional nature and to interpreting the dynamic processes that control these variations.

Requirements to Meet the Challenges

The report "Seismological grand challenges in understanding Earth's dynamic systems" describes the detailed seismological approaches and practical requirements needed to make progress in attacking each of the 10 grand challenges. A number of common themes emerge in terms of these approaches and needs. For example, increasingly massive data sets, inversions for 3-D and 4-D multiscale models, and realistic simulations incorporating as much of the physics as possible require enormous computational capabilities. Thus, collaborative efforts to increase access to state-of-the-art computing are essential. Another such theme is seismology's long tradition of open access to all data sets and storage of these data sets in perpetuity; this approach needs to be encouraged and supported globally. Networks of permanent, broadband, real-time observatories form a backbone of national and worldwide monitoring efforts, and these networks need to be maintained, upgraded, and, where possible, expanded to the oceans.

An essential need for several of the grand challenges is the availability of large pools of portable instruments for seismological investigations of continental and oceanic environments at higher resolution than that afforded by the current global network of permanent stations. The pools of three-component, short-period, and broadband sensors need to be expanded, in the oceans and on land, for the next generation of 3-D and 4-D imaging efforts of crustal, lithospheric, and deep mantle and core structure.

In addition, a new facility should be established to make controlled seismic sources for land studies more available to the academic community. Further, the new seagoing R/V *Marcus G. Langseth* (owned by NSF and operated by Lamont-Doherty Earth Observatory of Columbia University) needs to be fully supported in a way that makes its 3-D imaging capabilities more readily accessible to investigators.

There is a common need for the development and coordination of advanced data products to make the results of seismological research more accessible to the public and to Earth scientists in other disciplines. Finally, strong synergisms within the Earth science arena between seismology and other disciplines need to be fostered and strengthened. Progress on the seismological grand challenges noted here, and on the many societal applications of seismology, hinges on improved interdisciplinary interactions and communications, in addition to the shared, practical requirements described above.

—DONALD W. FORSYTH, Brown University, Providence, R. I.; E-mail: donald_forsyth@brown.edu; THORNE LAY, University of California, Santa Cruz; RICHARD C. ASTER, New Mexico Institute of Mining and Technology, Socorro; and BARBARA ROMANOWICZ, University of California, Berkeley

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Probing the Hawaiian Hot Spot With New Broadband Ocean Bottom Instruments

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The Hawaiian hot spot is regarded as the textbook example of the product of a deep-rooted mantle plume [*Wilson,* 1963; *Morgan,* 1971]. Its isolated location, far from any plate boundary, should provide an opportunity to test most basic hypotheses on the nature of plume-plate interaction and related magmatism [e.g., *Ribe and Christensen,* 1999]. Yet the lack of crucial geophysical data has sustained a debate about whether Hawaii's volcanism is plume-related or is instead the consequence of more shallow processes, such as the progressive fracturing of the plate in response to extensional stresses [*Turcotte and Oxburgh,* 1973].

In the plume model for Hawaii's volcanism, hot material is expected to ascend near vertically within the more viscous surrounding mantle before ponding and spreading laterally beneath the rigid lithosphere. Mantle convection in general, and the fast moving Pacific plate in particular, shear and tilt the rising plume. The plume top is dragged downstream by the plate, and this dragged material may give rise to an elongated bathymetric swell [*Davies,* 1988; *Olson,* 1990; *Sleep,* 1990; *Phipps Morgan et al.*, 1995]. However, identifying the dominant cause of the swell remains elusive, and proposed mechanisms include thermal rejuvenation, dynamic support, compositional buoyancy, and mechanical erosion (see *Li et al.* [2004] for a summary). There is also considerable debate about the continuity of the plume within the mantle, how discrete islands are formed, and how a deep-rooted plume interacts with the mantle transition zone [e.g., *van Keken and Gable,* 1995].

Seismic Imaging of Hawaiian Mantle

Seismic imaging can help distinguish among plausible models, but the deployment of seismic stations that has been limited to the nearly aligned Hawaiian Islands has so far led to incomplete images of the crust and mantle beneath and around Hawaii. The Hawaiian Plume-Lithosphere Undersea Mantle Experiment (PLUME) is a multidisciplinary program whose centerpiece is a large network of four-component broadband ocean bottom seismometers (OBSs) and three-component portable broadband land stations (Figure 1). Occupying a total of 82 sites and having an overall aperture of more than 1000 kilometers, this experiment is one of the first large-scale, long-term deployments of the new broadband OBSs in the U.S. National Science Foundation–supported national OBS Instrument Pool (OBSIP). PLUME is providing an opportunity to use the full range of seismic techniques that have been applied successfully in land-deployed experiments. Body wave and surface wave tomographic imaging as well as receiver function and compliance analyses will provide new constraints on elastic and anelastic seismic structure and major discontinuities from crustal depths into the lower mantle. The analysis of shear wave splitting and surface wave azimuthal anisotropy will help reveal mantle fabric and flow patterns.

Now, about 18 months after the last OBSs were recovered from the ocean floor, the high overall return and quality of PLUME data allow for the production of

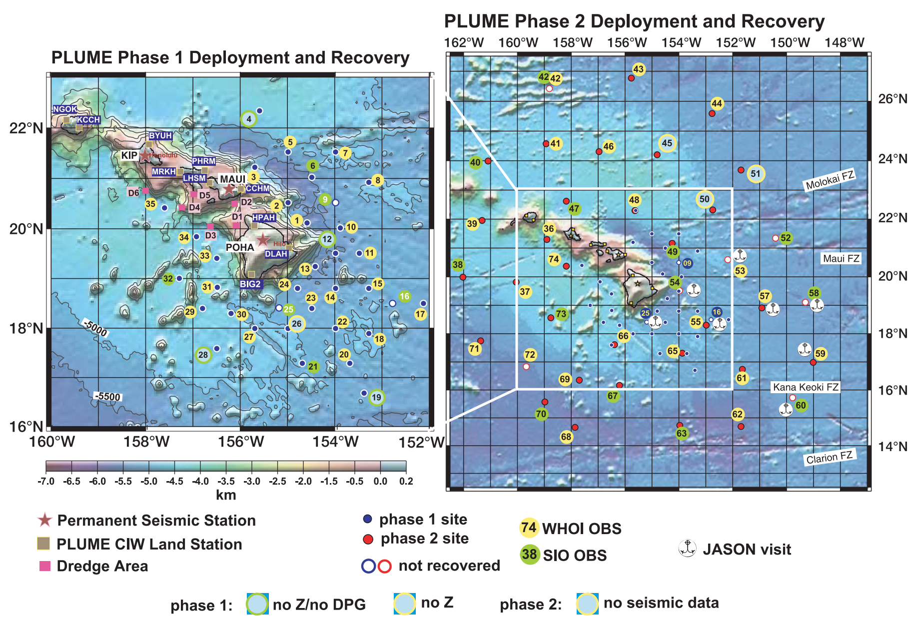

Fig. 1. Site locations of the two deployment phases of the Hawaiian Plume-Lithosphere Undersea Mantle Experiment (PLUME). Also shown are sites of permanent stations of global seismic networks relevant to this study. Station KIP (Kipapa, Oahu) is jointly operated by the French Geoscope program and the U.S. Geological Survey (USGS); POHA (Pohakuloa, Hawaii) is operated by USGS; and MAUI is operated by the German Geo-ForschungsNetz (GEOFON). USGS station MIDW (Midway; see Figure S1 in the electronic supplement) is not shown. Phase 1 operated from January 2005 through January 2006, and phase 2 operated from April 2006 through June 2007. Two sites with unrecovered ocean bottom seismometers (OBSs) from phase 1 and six sites from phase 2 were visited by Woods Hole Oceanographic Institution's remotely operated vehicle (ROV) Jason *in November 2007. The OBSs at sites 57 and 59 were recovered at that time. Four sites with five lost OBSs (sites 9; 42, with two OBSs; 52; and 72) remain unvisited. Open numbered circles mark instruments with a loss of differential pressure gauge ("no DPG") and/or vertical-component seismometer data ("no Z"). During the first deployment cruise, 11 dredge hauls were performed at six locations to retrieve fossil corals and deep-rift volcanic rocks.*