

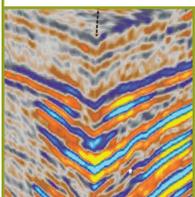
SEISMOLOGICAL GRAND CHALLENGES IN UNDERSTANDING EARTH'S DYNAMIC SYSTEMS

IN EARLY 2009, the US academic seismology community published “Seismological Grand Challenges in Understanding Earth’s Dynamic Systems.” Intended partly as a plan for seismological research over the next five to ten years, the report documents numerous ways in which seismology serves society and contributes to economic development. This summary for policy-makers highlights the social benefits from seismological research and lists some investments for seismological research and education—carried out in universities, the private sector, and government agencies—that are required to make further progress.

MONITORING THE ENVIRONMENT



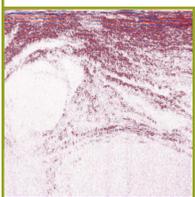
GAS HYDRATES. Gas hydrates may temporarily remove methane from the carbon cycle only to release it suddenly as the environment changes. Seismic reflection is an effective tool for large-scale mapping of gas hydrates frozen in the soil beneath shallow oceans while high-resolution, three-dimensional seismic images show the plumbing system that feeds gas hydrate deposits. Waveform modeling can identify local concentrations and temporal changes in gas hydrates can be monitored through repeat surveys. *(sidebar 8, page 23)*



IMAGING CARBON STORAGE. When CO₂ is injected into deep rock layers to isolate it from the atmosphere, it is critical to assess where the gas goes and how effectively it is contained. High-resolution, three-dimensional seismic imaging offers key information on impermeable rock layers and subsurface geology for identifying viable structures for sequestration. Repeat (four-dimensional) imaging detects time-dependent changes for monitoring injection and migration. *(sidebar 15, page 35)*



CRYOSEISMOLOGY. Seismological techniques are used to study the tectonic evolution of West Antarctica and the history of ice cap changes; tidally modulated motion of ice streams in West Antarctica; the collisions and break-up of Earth’s largest ice shelves and icebergs; glacial calving; and a newly observed class of remotely detectable events from major tidewater outlet glaciers in Greenland. *(sidebar 11, page 30)*



IMAGING OCEAN STRUCTURE. The ocean’s fine structure is usually mapped by lowering instruments that measure temperature and salinity, but this slow process limits the volume of ocean that can be sampled and has constrained horizontal resolution. Marine seismic profiles can rapidly map boundaries between water masses, revealing layers as thin as 5 m with unprecedented lateral resolution and imaging kilometer-scale eddies that are thought to play a major role in ocean mixing. *(sidebar 12, page 31)*

REQUIREMENTS TO MAKE PROGRESS

- Develop new methods for data processing and quantification of material properties.
- Create source facilities and inexpensive sensors for high-resolution, 4D characterization of the shallow subsurface.
- Sustain global seismic observations and make more acoustic data openly available for basic research.
- Install permanent polar seismic networks and acquire many portable, low-temperature-capable geophysical instruments.

MITIGATING NATURAL HAZARDS



TREMOR AND SLIP. In the past decade it was discovered that collisions between continental and oceanic plates can be accompanied by intervals of regular seismic tremor and slow fault slip that are not generally felt by the local population. The new picture of the fault zone suggests that the probable regions of strong ground motion during future earthquakes at active continental margins extend significantly further inland than had been thought, closer to large population centers. (*sidebar 4, page 15*)

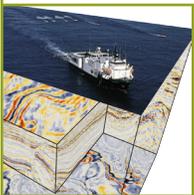


WASTE REPOSITORY SITING. National Seismic Hazard Maps provide a probabilistic assessment of strong ground motions for any location across the United States and drive the design criteria for new construction. Advances in understanding the physics of earthquake rupture, combined with massive computational capabilities, allow exploration of the range of physically plausible ground motions beyond levels in the brief historical record. (*sidebar 10, page 27*)



MONITORING VOLCANOES. New methods using seismic “noise” reveal seismic velocity changes that are likely caused by opening of near-surface cracks in the volcanic edifice as it is inflated by increased pressure within the underlying magma chamber. Maps of the velocity changes show that different parts of volcanoes are affected in the precursory activity leading up to different eruptions. (*sidebar 16, page 39*)

DISCOVERING AND MAPPING NATURAL RESOURCES



EXPLORING FOR ENERGY AND MINING. The petroleum industry relies on high-resolution, three-dimensional seismic surveying to map oil and gas reservoirs with the detail necessary to image the faults and complex sedimentary features that can trap energy reserves. Four-dimensional (or time-lapse) imaging requires repeat surveys to monitor reservoir mechanical and fluid changes during resource extraction. These surveys are increasingly accompanied by monitoring of production-induced microearthquakes. Three-dimensional seismic reflection imaging has delineated coal-bed methane deposits, and its use is likely to grow as easily accessible deposits are exhausted. Pioneering work adapting seismological techniques to nonlayered and steeply dipping targets in crystalline rocks has proven valuable for mapping mineral deposits. (*sidebar 13, page 33*)

REQUIREMENTS TO MAKE PROGRESS

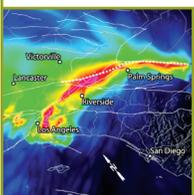
- Sustain long-term operation of global and regional networks and deploy offshore geophysical observatories.
- Deploy borehole seismographic arrays near faults and a large network of strong ground motion recorders.
- Maintain many portable instruments for rapid network deployment and post-event fault drilling after earthquakes.
- Conduct 4D active-source and ambient noise studies of volcanoes and reservoir systems.

BUILDING A SCIENTIFICALLY AND TECHNOLOGICALLY PROFICIENT WORKFORCE



WORKFORCE ISSUES. The US Department of Labor and others have documented the national need for well-trained geoscientists, but too few students are being trained to fill the vacancies left by our aging workforce. By 2020, the petroleum industry alone expects to fall short by 20,000 geoscientists. The need for energy, environmental protection, and responsible land and water management is expected to further spur employment demand. Undertakings in seismology require talented people with solid quantitative skills who have undergraduate and graduate training in fundamentals and applications of scientific theory. (*sidebar 14, page 34*)

MOTIVATING ADVANCES IN COMPUTERS, NETWORKING, AND COMMUNICATIONS

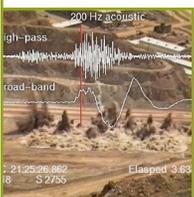


PREDICTING GROUND MOTIONS. Physics-based strong ground motion simulations are needed because there are very few on-scale recordings near large earthquakes, where the hazard is highest. Such simulations must properly account for stress and slip evolution at spatial scales spanning many orders of magnitude and accurately reflect nonlinear Earth behaviors. They require the use of today's most powerful supercomputers. (*sidebar 6, page 18*)



EARTHQUAKE RAPID WARNING. With sufficient investments to link seismic networks with civil decision-making systems, a warning can be provided that comes before strong shaking starts at a location. Before a future earthquake, a person might get enough warning to dive under a table, trains could slow or stop, nuclear power plants could lower their control rods, and refineries could isolate tanks and vulnerable pipelines. (*sidebar 2, page 13*)

CONTRIBUTING TO NATIONAL SECURITY

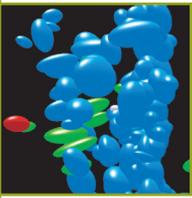


MONITORING NUCLEAR EXPLOSIONS. Seismology plays a key role in detecting and characterizing nuclear explosions and discriminating explosions from earthquakes and other seismic-wave-generating phenomena such as underground collapses. Operational and basic research in support of nuclear monitoring is carried out by a worldwide contingent of seismologists in universities, national laboratories, government agencies, and private companies. (*sidebar 7, page 20*)

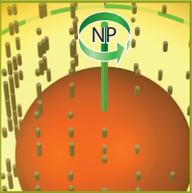
REQUIREMENTS TO MAKE PROGRESS

- Develop university-industry partnerships to publicize seismological career options and draw students to the field.
- Develop and disseminate improved numerical methods to simulate wave propagation; broaden access to supercomputers.
- Provide further resources and development for real-time analysis of earthquake sources.
- Increase and stabilize funding for explosion monitoring research to sustain national capabilities.

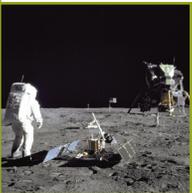
ASPIRING TO A DEEPER UNDERSTANDING OF OUR WORLD



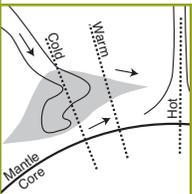
DEEP EARTHQUAKES. Sliding along a dry fault should be prohibited by the tremendous pressures at depths greater than 50 km, which would cause the frictional resistance to sliding to exceed the strength of rock. Yet, earthquakes are observed down to depths of 700 km. Different hypotheses make predictions that can be seismologically tested but specially designed deployments are necessary. (*sidebar 19, page 49*)



THE MYSTERIOUS INNER CORE. Recent seismic analyses have revealed three-dimensional structure within the inner core at multiple spatial scales, with variations over several decades. Multidisciplinary studies can build on these discoveries to shed light on the mechanism of inner core growth by progressive freezing, which generates energy to maintain Earth's magnetic field and is critical to the thermal evolution of the core and the cooling history of the planet. (*sidebar 20, page 52*)



PLANETARY SEISMOLOGY. Seismic data from the Apollo program revealed unique and fundamental information about the Moon's internal structure. Return of lunar seismometers would provide opportunities to explore outstanding basic questions, such as, was the Moon formed from ejecta of a large impact on Earth? Deployments of seismometers on other planetary bodies might address many significant questions, including the extent of water within the crust of Mars. (*sidebar 21, page 54*)



CORE-MANTLE BOUNDARY HEAT FLOW. About 25 years ago, seismologists discovered a jump in seismic velocity several hundred kilometers above the core-mantle boundary. This jump remained enigmatic until 2004, when mineral physicists discovered that the dominant lower mantle mineral transforms to a new phase at corresponding pressures and temperatures. Details within the formerly enigmatic layer have broad implications for mantle convection, core cooling, and inner core growth. (*sidebar 22, page 58*)

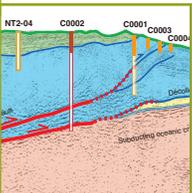
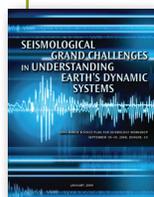


PLATE BOUNDARY FIELD LABORATORIES. Dense geodetic instrumentation, high-resolution 3D imaging, and deep drilling into active fault zones are essential approaches to understanding complex plate boundary systems. Structure and deformation models from seismic and geodetic data, rock samples and in-situ rock properties from drill holes, and signals from small earthquakes reveal fault properties that control the transition between smooth sliding and slip primarily in earthquakes. (*sidebar 18, page 48*)

REQUIREMENTS TO MAKE PROGRESS

- Deploy long-term integrated geophysical observatories in multiple plate boundary environments.
- Expand global coverage with state-of-the-art seismic stations, including the ocean basins.
- Deploy large portable arrays to resolve anisotropy and fine-scale heterogeneity deep in the Earth.
- Include seismic data acquisition in planetary exploration efforts.



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