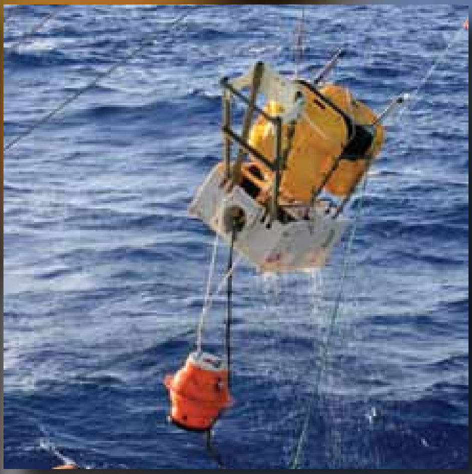
Report on the

Experiments With Portable Ocean Bottom Seismographs Workshop



September 26–28, 2010 | Snowbird Resort, Utah

WORKSHOP CONVENERS

Richard Allen, University of California, Berkeley

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SPONSORS

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Experiments With Portable Ocean Bottom Seismographs

Workshop

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Introduction

From September 26 through September 28, 2010, approximately 75 individuals from nine countries and 39 institutions met in Snowbird, Utah, to examine the future of ocean bottom seismology using portable instrumentation to study problems in Earth structure and dynamics. The Experiments with Portable Ocean Bottom Seismographs (EPOBS) Workshop included representatives from the Incorporated Research Institutions for Seismology (IRIS) and the National Science Foundation (NSF), researchers, instrument manufacturers, and the Institutional Instrument Contributors (IIC) of the Ocean Bottom Seismometer Instrument Pool (OBSIP). Workshop conveners were Richard Allen (University of California, Berkeley), Don Forsyth (Brown University), Jim Gaherty (Lamont-Doherty Earth Observatory), John Orcutt (Scripps Institution of Oceanography), Doug Toomey (University of Oregon), and Anne Trehu (Oregon State University). Throughout the workshop there were stimulating discussions of many topics, including highlights from past experiments; instrument deployment and development opportunities; a comparison of principal investigator, open-access, and community-driven experiments; science opportunities for ocean bottom seismology; international cooperation; and future directions for the community. A detailed agenda and list of attendees can be found at http://www.iris.edu/hq/obs_workshop.

The overarching objectives of this community-based workshop were to:

- Identify the long-term goals and scientific opportunities for research in Earth's ocean using portable seafloor seismological instrumentation
- Identify the science and user requirements to be met by facilities and infrastructure that would support experiments addressing these goals
- Explore new technologies that shall have significant impacts on seafloor seismology and the ability to support a broad range of science
- Identify strategies for maximizing the scientific return and efficient use of facilities, including the development of open, community initiatives
- Increase the size and vigor of the research community that routinely uses marine seismic data

On the afternoon before the EPOBS meeting, 24 prior users of the OBS IICs and representatives from each of the IICs met for the afternoon to discuss their experiences with the facilities and make recommendations for the future. The main objective was to discuss what has worked well and what has been problematic during experiments serviced by OBSIP over the past decade, focusing on improvements to procedures, communications, and instrumentation to increase the success of future experiments. We hope to build on our collective experience as we embark on a new generation of instruments, experiments, and users. The retreat report can be found at http://www.obsip.org.

Science Opportunities

Subduction Zones

The study of almost all subduction-related processes requires the use of ocean bottom seismometers. Approximately 50% of all volcanic arcs are oceanic (**Figure 1**). In addition, the trenches and major portions of the subduction zones associated with terrestrial arcs are also offshore. While significant advances in our understanding of seismicity, melting, metamorphism, and subduction zone mantle flow have been made with onshore deployments across volcanic arcs, insufficient instrumentation for offshore deployments is currently a limiting factor. Onshore deployments have imaged the detailed structure of the subducting plate, the mantle wedge, and the overriding plate. Accurate constraints on seismicity, seismic velocity, anisotropy, and attenuation all provide critical constraints on structure and processes. Efforts to extend seismic velocity constraints offshore, and to locate seismicity, are all limited by the absence of seismic data recorded on the ocean floor, directly above the region being studied. The situation for oceanic arcs is even worse. With onshore deployments (on the arc itself), only a very limited portion of subduction-related processes can be studied. It is important to study ocean-ocean convergence in its own right, but also to compare and contrast the effects of overriding continental lithosphere with overriding oceanic lithosphere.

Instrumentation Needs

To provide answers to some of the outstanding scientific questions related to subduction zone processes, additional ocean bottom seismometers are needed to expand the scope of offshore deployments. Most of the studies to date have been individual lines of instruments. This deployment strategy has dominated onshore and the few offshore studies of subduction zones and is due to limited resources. However, it is clear that subduction zone processes are three dimensional and, therefore, two-dimensional grid-type deployments are needed to constrain structure both down dip and along strike. It is also necessary to link onshore and offshore studies. The Amphibious Array Facility (AAF) that has been built and is being deployed in Cascadia is an example of the kind of deployment needed in subduction zone environments. It will provide a continuous set of constraints onshore and offshore across (and along strike of) the entire subduction zone. Both shallow- and deepwater instrumentation are needed. Shallow-water instrumentation was largely absent from OBSIP until creation of the AAF. However, additional shallow-water instruments will likely be needed in the future.

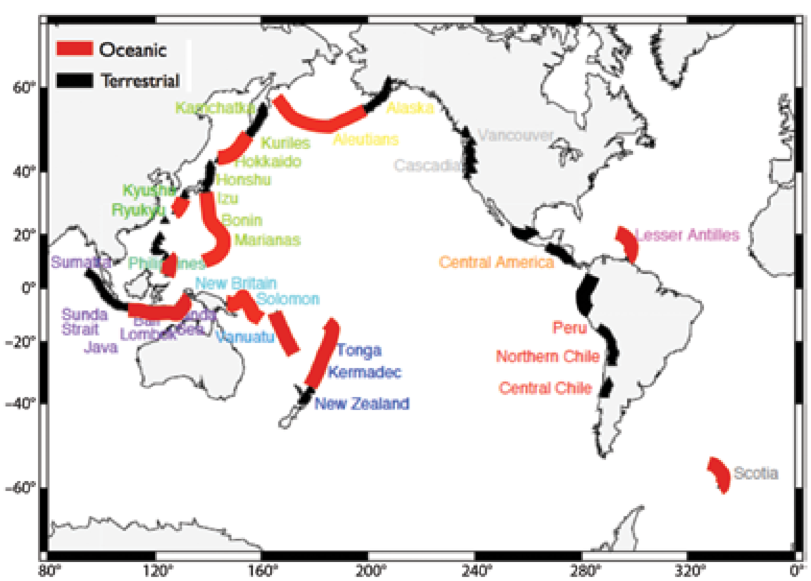

Figure 1. Map of volcanic arcs around the Pacific. Approximately 50% are oceanic. Significant portions of the subduction zones associated with the terrestrial arcs are also beneath the ocean. OBS deployments are essential for studying subduction zone processes. Figure courtesy of G. Abers.

Thrust Zone Processes

The last decade has seen a remarkable expansion in the range of seismicity observed in subduction zones. Our view of subduction zone seismicity used to consist of simple double-couple earthquakes that defined the Wadati-Benioff zone and outlined the path of the subducting plate. Today, in the shallow portion of the subduction zone, we see "normal" megathrust earthquakes, very low-frequency earthquakes, seismic tremor (nonvolcanic tremor), slow earthquakes, afterslip, and long-term creep (Figure 2). This range of seismic events, and the range of spatial-temporal deformation that generates them, is now providing a detailed and complex picture of the thrust zone.

Starting at depth, the subducting plate slides stably. Moving updip, there is a transitional zone between the stable sliding and unstable megathrust region. In this transitional zone, we observe episodic tremor and slip (ETS). The discovery and investigation of ETS is perhaps one of the most exciting developments in seismology in the last decade as it is a "predictive" seismic process (i.e., it has a regular recurrence interval on the time scale of months, and it is observed on the thrust interface adjacent to the megathrust region). Continuing updip from the megathrust, there may be another transitional zone between the megathrust and the stably sliding portion of the thrust adjacent to the trench (Figure 3). Therefore, we expect a similar range of seismic events updip of the megathrust. This region is offshore for terrestrial (and oceanic) subduction zones. The ability to detect tremor, slow earthquakes, very low-frequency earthquakes, and perhaps slow slip and creep in this region is crucial to understanding megathrust processes. As the megathrust usually spans the coastline in terrestrial subduction zones, these studies also have significant implications for seismic and tsunami hazards. As we now know from the great 2011 Tohoku earthquake, the toe of the subduction zone immediately adjacent to the trench does not always slip stably and is capable of very large displacements during an earthquake (as much as 50 m). This tsunamigenic earthquake adds greater urgency to the offshore study of subduction zones such as Cascadia.

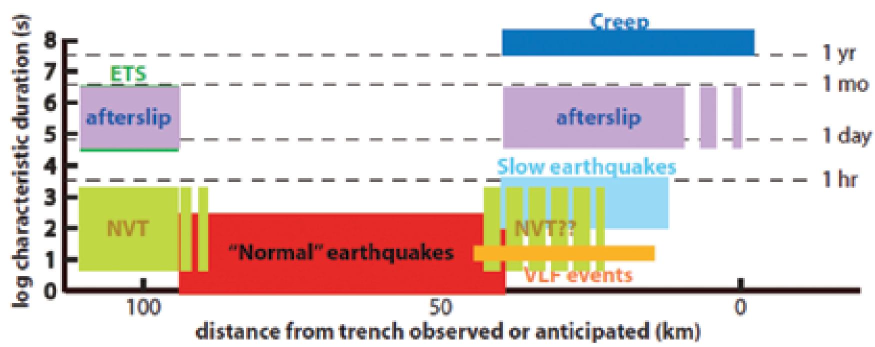

Figure 2. Illustration of the range of seismic/deformation events in subduction zones. From the MARGINS Decadal Review (2009).

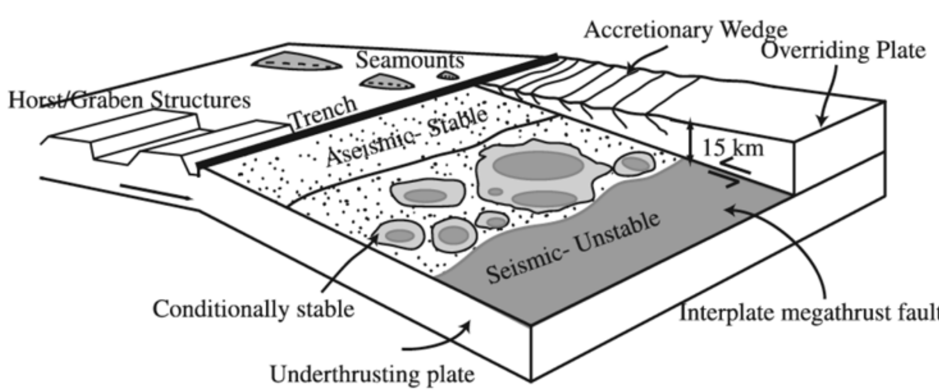

Figure 3. Conceptualized view of the structure and processes on the subduction interface from the megathrust updip to the trench. These processes, and the seismicity that they generate, are largely offshore even for terrestrial subduction zones. From Bilek and Lay (2002).

The central questions that require OBS deployments thus include: What controls the updip and downdip limits, and the patchiness, of megathrust faults? Over what timescales does slip occur, and what regulates this variability? What is the geometry of the thrust fault, and are there fault splays? Does the downgoing plate structure regulate seismicity? Are there other types of seismic source as yet undetected?

Volatile Cycling

One of the fundamental questions in solid Earth science is how much water is contained within the mantle? The fraction of H_2O and other volatiles in the mantle is a crucial determining factor in melting processes in all environments, including in the arc. Volatiles are highly incompatible and are rapidly removed from the mantle during melting. Therefore, the controlling factor in the concentration of volatiles in the mantle is the input of volatiles to the deep mantle at subduction zones. The volumes of H_2O in the lithosphere of the subducting plate remain largely unknown, while the effect of hydration on observables such as seismic velocities is substantial. Therefore, there is the potential to make significant progress on this topic with additional seismic data.

The first half of the water budget is the input to the subducting plate. This input occurs through alteration of the plate close to the ridge, sedimentation on the ocean floor as it approaches the trench, and additional alteration due to faulting in the outer rise adjacent to the trench as the plate bends. The largest potential reservoir, and uncertainty, is the degree to which faulting at the outer rise extends into the subducting plate lithosphere, and the degree of lithospheric serpentinization as a result. Recent work offshore of Nicaragua and Chile provides evidence for normal faulting and hydrothermal alteration extending into the lithospheric mantle. It is unknown the degree to which such alteration occurs in other locations.

Once the plate passes the trench, the process is reversed and H_2O is removed from the subducting plate through a variety of processes at different depths (**Figure 4**). At shallow depths, beneath the accretionary prism, fluid is

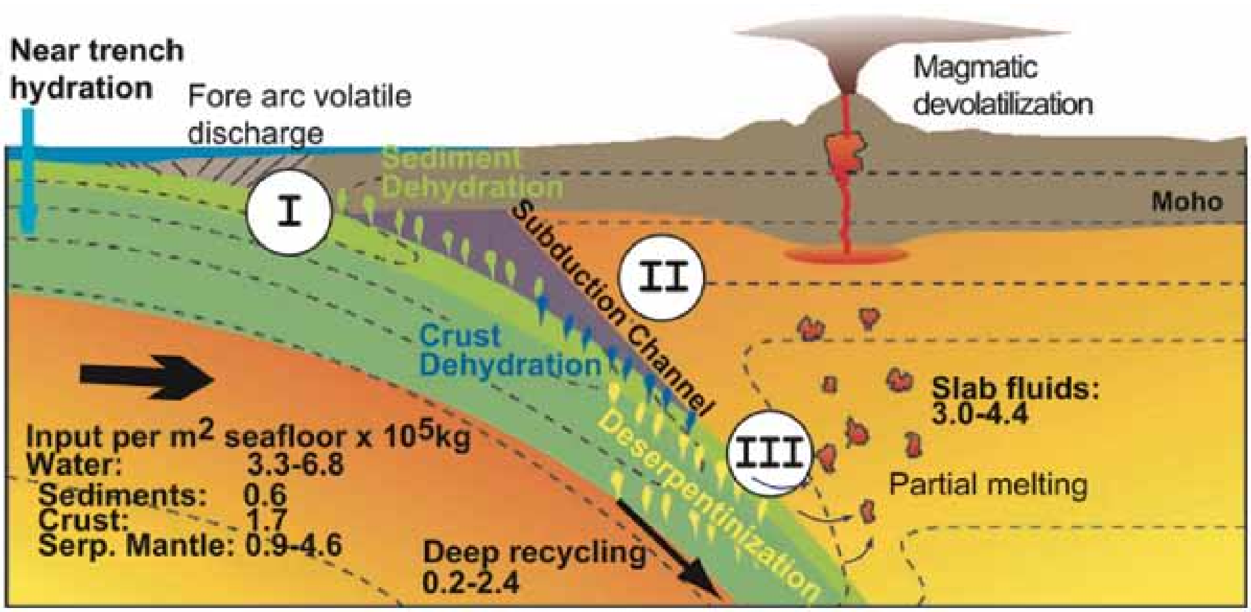

Figure 4. Schematic drawing of the subduction zone water cycle. Water is chemically bound within the incoming plate's sedimentary, crustal, and mantle portions. Slab fluid release can be divided into three stages: (1) shallow fluid release occurs at depths < 20 km from subducting sediments and may be related to fluid expulsion at cold vent sites in the fore arc region; (2) intermediate-depth (20–100 km) water release from sediments and oceanic crust may lead to cold upwelling along the "subduction channel"; and (3) deep fluid release (> 100 km) from oceanic crust and deserpentinizing mantle triggers arc melting. Some fraction of the incoming plate's initial water content is retained and recycled to greater mantle depths. Contour lines illustrate schematically temperatures at a subduction zone. From Rüpke et al. (2004).

removed by low-temperature discharge in the forearc. From ~ 20–100 km depth, fluid is released and causes serpentinization of the mantle wedge and possible cold upwelling along the subduction channel. Finally, around 100 km depth, deep fluid release, from the subducting crust and deserpentinization of the mantle, causes melting beneath the arc. The volatiles that remain make their way down into the deep mantle. While significant progress has been made constraining the serpentinization and melting process beneath terrestrial arcs, OBS deployments are needed to constrain the inputs at the outer rise and balance the volatile budget.

Magma Processes

Arc magmatic processes are believed to be the primary mechanism through which continental lithosphere is generated. Yet, how this process operates remains largely unknown. The mobilization of fluids in the subducting plate around 100 km depth is a global observation despite the range of temperatures of the subducting plate. Magmas are generated in broad zones through dehydration of the slab, while they erupt in discreet volcanic centers along the arc. The process of localization during the path from formation to eruption is a high priority for subduction zone studies, and the role volatiles play is key.

It is not known whether melt ascends as porous flow through the mantle wedge, or as buoyant plumes of material that advect through the wedge (Figure 5). With porous flow, melt is transported nearly vertically from the point of formation to the base of the overriding lithosphere. The process of localization must therefore occur at the base of the lithosphere and through the lithosphere. In the case of buoyant plumes, localization occurs in the wedge immediately above the melting region, and the location of melt may be further modified by the lithosphere at the surface.

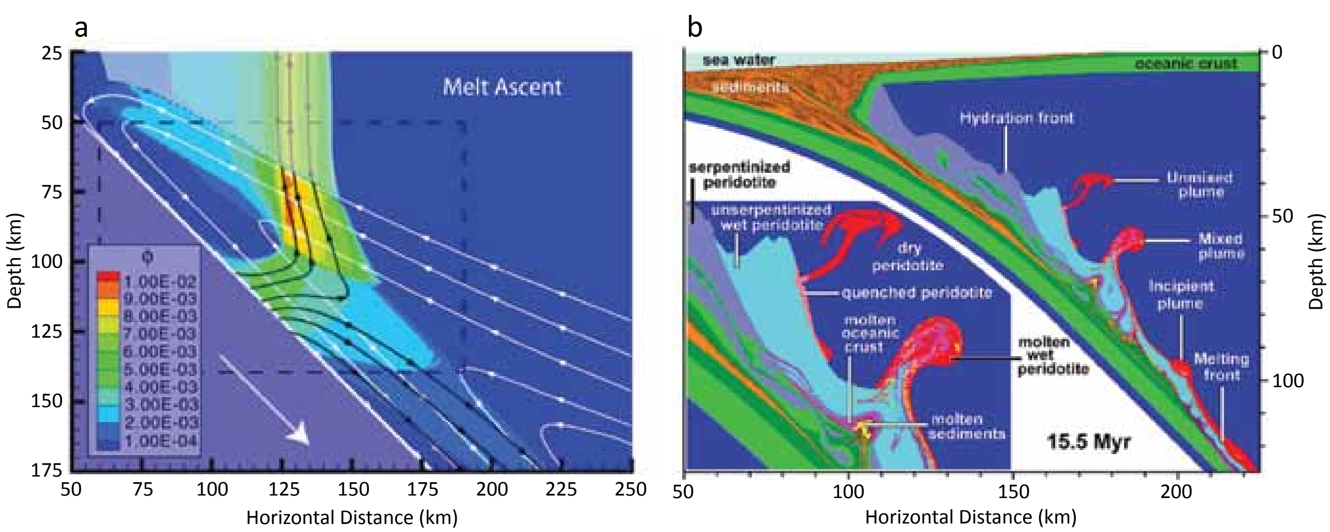

Figure 5. Alternative models of material transport from melt formation at the subducting plate interface up to the base of the overriding plate lithosphere. (a) Porous flow model from Cagnioncle et al. (2007), and (b) buoyant flow model from Gerya et al. (2006).

Earthquake Mechanics/Fault Studies

How do faults slip? was the first of the 10 Seismological Grand Challenges identified in the report of a 2008 workshop on seismological research frontiers funded by NSF (Lay, 2009). Recent observations have revealed a rich spectrum of fault slip behavior, ranging from steady creep, to faults that slip sporadically in sequences of numerous overlapping events, to faults that slip only in major earthquakes. To understand the physical factors that control fault behavior requires studying the structure and slip patterns in detail in a number of different tectonic settings. The importance of ocean bottom studies is obvious; approximately 90% of the world's plate boundaries are in the ocean.

The locked portion of subduction zones that tend to slip in major, damaging earthquakes extends well seaward of most coasts or island arcs. At the downdip end of the locked zone in the transition to the creeping or steady deformation regime at depth, episodic tremor and slip have been observed in several subduction zones, such as Cascadia and Japan (Figure 6). It is not known whether such events occur at places within the overall locked zone or whether they are found at the updip transition to the easily deformed toe of the overriding plate. Larger events offshore are easily detected on land, but microearthquakes and episodic tremor activity are not. Ocean bottom seismometers are needed to detect and locate these events. The Cascadia experiment beginning in 2011 will use an amphibious array of onshore and offshore seismographs to investigate the structure and seismic activity in this megathrust zone that has been the site of great ($M_w \geq 9$) earthquakes in the past and which poses perhaps the greatest seismic and tsunami hazard in the United States.

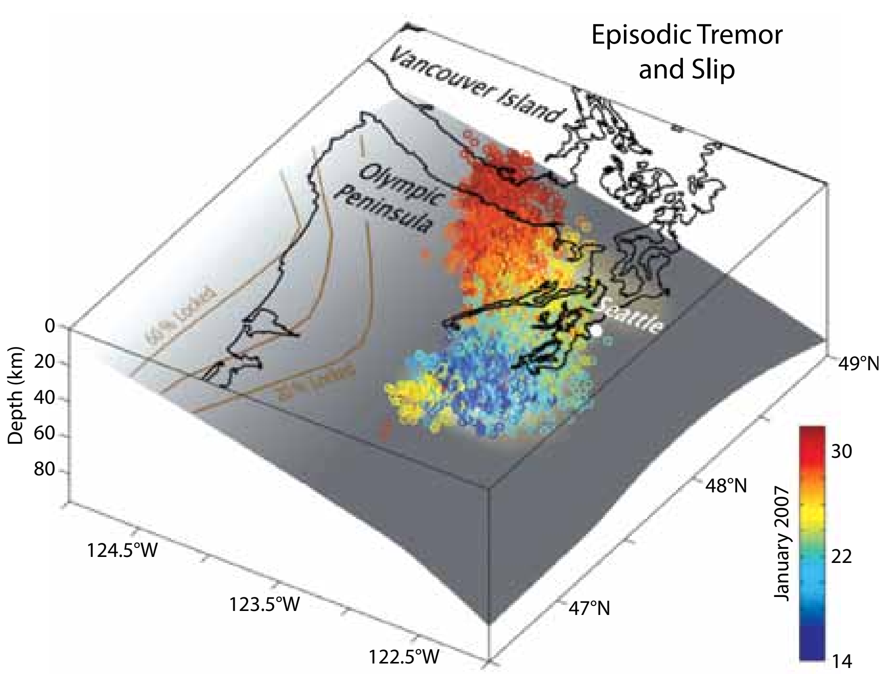

Figure 6. Location of migrating tremor during a two-to-three week episode of slow slip on the Cascadia subduction zone. Most of the relative plate motion in the slow-slip area is accommodated by similar slip events that repeat approximately every 14 months. Plate boundary slip in the "locked zone" to the west of the contours of partial locking occurs during great earthquakes such as the magnitude ~ 9 Cascadia megathrust earthquake in 1700. Image courtesy of A. Wech and K. Creager.

Oceanic transform faults, at least on the fast-slipping East Pacific Rise, appear to differ somewhat in their behavior from their continental cousins, such as the San Andreas Fault. Oceanic transforms tend to slip more often and perhaps more regularly in smaller events than continental transforms, a smaller percentage of the slip is accommodated in earthquakes, and the larger oceanic events tend to be preceded by more premonitory seismic activity or are parts of earthquake swarms, perhaps accompanying major creep events. Coupled slip of two adjacent transforms over a period of hours has also been observed. Understanding why these faults behave differently is fundamental to understanding the spectrum of earthquake slip behavior.

A thorough study of fault behavior requires a variety of ocean bottom instrumentation, including geodetic measurements and strong-motion instruments as well as traditional broadband OBS with active and passive sources to reveal creep events, foreshock and aftershock sequences, slip propagation during larger earthquakes, and fault zone structure including temporal changes. A recent experiment on the Quebrada-Discovery-Gofar (QDG) fracture zone system at ~ 4°S on the East Pacific Rise was the first intensive, in situ fault zone investigation in the ocean. Taking advantage of relatively frequent, time-predictable earthquake sequences on this fast-spreading ridge, the investigators, led by Jeff McGuire, captured an M_w 6.0 strike-slip event on a strand of the Gofar transform within an array of seismometers and accelerometers, recorded the foreshock sequence leading up to it, measured detailed crustal structure in a cross section across the fault zone, detected velocity changes in the crust associated with the earthquake (Figure 7), and monitored aftershocks and a subsequent swarm in an adjacent part of the fault zone that appears to slip predominantly in creep events. They also gathered structural information across part of the Quebrada fault zone; in this area, there have been no $M_w \geq 5.5$ events in the last 20 years, in contrast to the rest of the QDG system, where M_w 5.5 to 6.0 events occur every four to six years. Although this initial experiment was quite successful, it will be necessary to have experiments deployed for longer time periods to capture an entire seismic cycle, seismometers that remain linear and unclipped for moderate-sized, nearby events, and a more thorough investigation of temporal and spatial variations in fault properties.

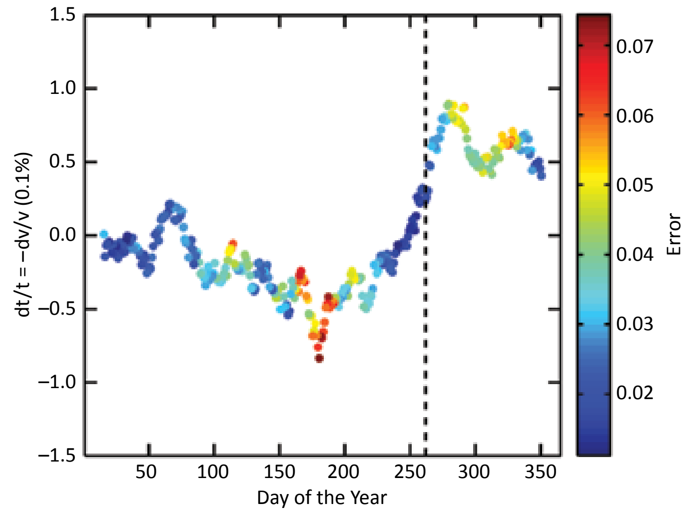

Figure 7. Changes in velocity of 1 s period Rayleigh waves associated with an M_w 6.0 earthquake on the Gofar transform fault (McGuire et al., 2012). Vertical dashed line indicates time of earthquake. Velocity or travel time is measured using ambient noise correlation between two sites on the fault. Note that the change in velocity or travel time appears to begin before the earthquake, suggesting it may be possible to make a short-term forecast of an impending event.

Normal faults are ubiquitous on mid-ocean ridges, although the scale of slip is much greater on slow-spreading centers like the central Mid-Atlantic Ridge than on fast-spreading or hotspot-influenced ridges. Seismicity on normal faults has been recorded teleseismically, in monitoring with widespread hydrophone arrays, and in relatively short-lived experiments with local arrays of OBS, but there have been no long-term experiments extending through a substantial part of an earthquake cycle nor detailed experiments focused primarily on fault zone properties. In the last decade, a number of oceanic core complexes (so-called megamullions) have been discovered that expose deep-seated rocks on fault surfaces extending up to tens of kilometers in the direction of spreading. These core complexes appear to form by continuous slip on relatively low-angle faults extending into a magmatic mush zone or magma chamber. They are most commonly formed at the inside corner of ridge-transform intersections at slow, but not ultraslow, spreading ridges, but as yet there is no understanding of why they occur in this particular tectonic setting. The mechanics of their formation remains an observational and theoretical challenge.

Deep Earth and Mantle Plumes

Many studies of convection and structure of the core and deep mantle are hindered by incomplete or uneven sampling of Earth's interior by seismic waves. Because convection is a global process, these holes in our coverage limit our ability to understand how heat is transferred in the mantle and how the core has evolved. Incomplete coverage is caused by the concentration of seismic sources along plate boundaries and in subducting slabs, and by the concentration of seismic stations on continents and islands, leaving large gaps in the ocean (Figure 8). Numerous recommendations over the last 20 years state that these gaps should be filled in either by long-term stations in boreholes or by leapfrogging arrays of stations deployed for one to two years.

In addition to filling in gaps in global coverage, studies of dynamic processes in Earth's deep interior require relatively dense arrays of seismographs to probe the structure of specific features, such as mantle plumes. A beautiful example of the power of arrays to illuminate deep structure is provided by the Plume-Lithosphere Undersea Mantle Experiment (PLUME) around Hawaii (Figure 9). There has been much debate in recent years about the origins of hotspots like Hawaii. Hawaii is the archetype hotspot with age-progressive volcanism that formed the basis for the plume hypothesis that hotspots originate in the deep mantle, perhaps near the core-mantle boundary. In recent years, however, there has been much debate about whether most, if not all, hotspots have shallow origins in the upper mantle. PLUME demonstrated that there are low seismic velocity anomalies indicative of high temperatures continuing at least hundreds of kilometers into the lower mantle (Figure 10), consistent with a plume origin. It also found that the vertical extent of anomalously low velocities left behind the plume in the upper mantle beneath the Hawaiian swell extended to greater depths than expected. But even the PLUME array, the largest, long-term experiment with ocean bottom seismometers to date, provided insufficient lateral coverage to determine whether the plume extends all the way to the core-mantle boundary.

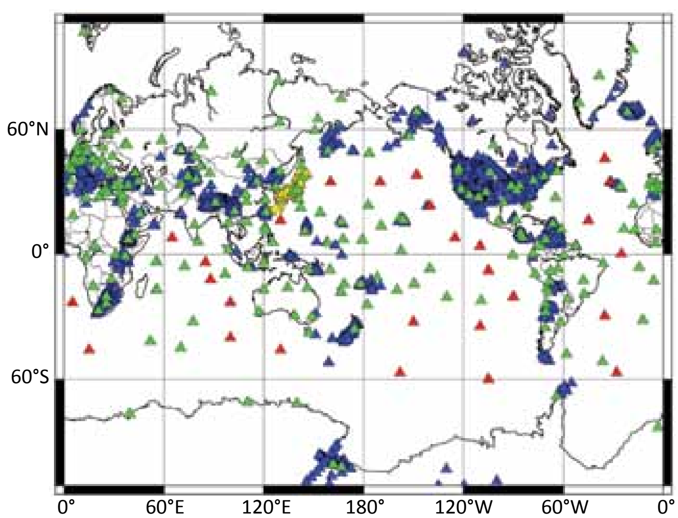

Figure 8. Distribution of seismic stations. Red triangles: possible locations of ocean bottom instruments to fill in gaps left by land stations. Green and yellow: Global Seismographic Network, Japan network, and other permanent stations. Blue and black: deployments of broadband instruments in array experiments. From S. Tanaka presentation, EPOBS workshop.

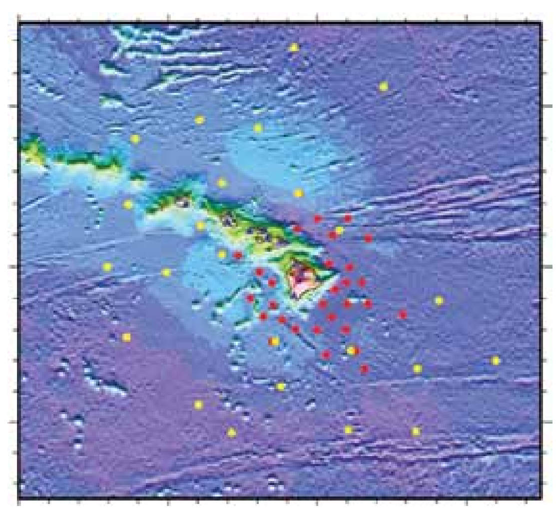

Figure 9. Distribution of broadband ocean bottom seismometers in the PLUME experiment around Hawaii. Red: first deployment. Yellow: second deployment. Blue: island stations.

There are many remaining scientific challenges to understanding the dynamics of the deep Earth that will require investigation with ocean bottom seismographs. Some of these opportunities are described below.

Mantle Plumes and the Origin of Hotspots

Basic information needed to understand the dynamics of hotspot formation and mantle flow is the depth extent, location, and tilt of any low velocity zones in the mantle beneath the hotspot. Although it appears that the Hawaiian hotspot does indeed have a lower mantle origin, other hotspots may not. It has been suggested, for example, that the Azores is really a wet spot rather than a hotspot. Many of the major hotspots are in the ocean, perhaps because they may help to split continents apart. The Superswell region in the Pacific, including several hotspots forming island chains such as the Society Islands, Austral Islands, and Tuamotos, lies above one of the two global "superplume" structures in the lower mantle. The connections between the deep superplume and the hotspots is unknown as is the detailed structure of the superplume. Although there have been investigations of some of these hotspots with a combination of island stations and ocean bottom seismometers, all of these studies to date except PLUME have involved a relatively small number of instruments.

Structure of the Transition Zone

The transition zone between the upper and lower mantle plays a key role in mantle dynamics. The depth and sharpness of the seismic discontinuities within and at the top and bottom of the transition zone provide information about the temperature structure and composition of the convecting mantle, as they are caused by temperature-dependent phase changes. Subducting slabs are often deflected above the 660 km discontinuity, accumulating in the transition zone before plunging into the lower mantle. There is growing evidence that the transition zone may be a storage region for water in the mantle, because water is more soluble in the minerals found there than in the overlying upper mantle.

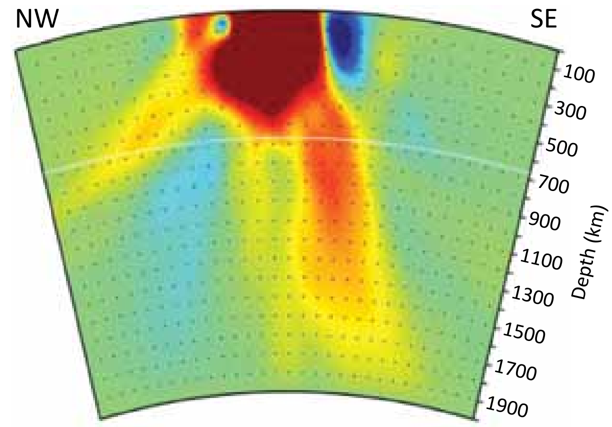

Figure 10. Shear velocity anomalies in a NW-SE cross section through the island of Hawaii (Wolfe et al., 2009). Red shades: slow. Blue: anomalously fast.

In some regions there may be aqueous fluid or melt immediately above the transition zone, where water-rich mantle has upwelled through the transition zone. We can probe the transition zone remotely using reflected phases such as SS recorded at land stations, but the information is low resolution. The best, most detailed data on transition zone structure come from stations immediately above the region of interest. Using OBSs, we can record converted phases, such as Sp and Ps, that provide direct sampling of the mantle discontinuities through receiver function analysis.

Core-Mantle Boundary

Other than the shallow lithosphere and asthenosphere, the region immediately above the core-mantle boundary (CMB) is the most heterogeneous part of the mantle. This lowermost part of the mantle is thought to be a thermal boundary layer created by heat lost from the core and by the halting of sinking cold mantle convection currents (or subducted slabs) at the CMB transition to the dense, liquid, metallic core. The CMB thus plays a crucial part in controlling the pattern of convection within Earth. Above the CMB, there is a high-velocity region of variable thickness, sometimes 200 km or more, that may represent a transition of lower mantle mineralogy to a post-perovskite phase. Beneath this high-velocity region, there are sometimes thin low-velocity zones that may represent a transition back out of the post-perovskite phase when the temperature gradients are high enough. In other areas, there are ultra-low velocity zones immediately above the CMB that appear to require melting of the lowermost mantle. Mapping of the global distribution of all these anomalous structures would provide extremely strong constraints on the form of mantle convection, but at present, our knowledge is limited to relatively few patches by the uneven sampling.

Core Structure

The rapidly convecting, liquid outer core appears to be remarkably homogeneous in structure, but several exciting discoveries have been made about the inner core in the past 10 to 15 years, including laterally variable seismic anisotropy, differential rotation of the inner core relative to the mantle, and seismic velocity variations in the lowermost outer core immediately above the inner core. The structure of the inner core provides clues to its evolution and Earth's secular cooling that resulted in inner core formation and growth. Structure of the region above the inner core should provide information about the pattern of convection in the core. As with the mantle, these studies are limited by lack of ray coverage. Many of the best regions for recording core phases lie in the ocean (**Figure 11**). Array studies are needed for precise resolution.

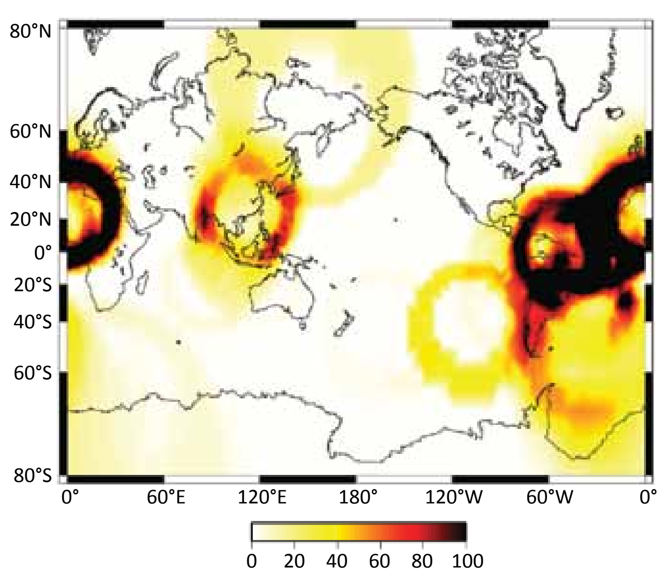

Figure 11. Relative density of predicted core phase arrivals. From S. Tanaka presentation, EPOBS Workshop.

Recommendations for Deep Earth Studies

Possible Community Experiments

1. A series of array deployments along the Mid-Atlantic Ridge from Iceland to the equatorial Atlantic. Targets would include deep structure of the Iceland and Azores hotspots, detailed study of upwelling beneath the segmented, slow-spreading ridge, and core phases in the southern North Atlantic. These areas are ideal for collaboration with European scientists. There is a good distribution of regional and teleseismic sources. The experiments would require ~ 100 instruments per year for 10 years (70–100 km spacing), denser in some areas for fine structure of the ridge. For source properties of local earthquakes, strong motion instruments are needed.

2. A plate-scale transect from a ridge to a continent. Possibilities include the North Atlantic, linking to EarthScope; the South Atlantic, linking to the African superplume/superswell; and the Juan de Fuca Ridge, linking to western North America. Such a study would include ridge structure, evolution of an oceanic plate, and the transition from ocean to continent, and might include a hotspot as well as generally augmenting lower mantle and core imaging.

3. The Ontong-Java Plateau. This Cretaceous feature is one of the largest oceanic igneous provinces with anomalously thick crust. There is debate about whether it was caused by the arrival of an upwelling plume head or by an impact of an extraterrestrial body that generated melting in the upper mantle. Its deep structure is virtually unknown except from global surface wave tomography and limited regional surface wave studies.

4. A large array or migrating sets of arrays in the South Pacific superswell region. These arrays could probe the structure beneath individual hotspots and reveal connections between these hotspots or connections of the hotspots to the deep Pacific superplume. Such a deployment would also provide details of the evolution of plate structure with time.

5. Leapfrogging arrays of seismometers to fill in gaps in global coverage. Global studies would benefit from longer-term deployments in gaps, but that approach might be impractical or very expensive except where cables are already available or in association with Ocean Observatory Initiative sites. Leapfrogging arrays would provide redundancy compared to single station installations and the added benefit of detailed local or regional resolution.

Technological and Methodological Developments

1. Buried sensors. Many standard techniques of earthquake seismology, such as shear wave splitting, receiver function analysis, and Love wave dispersion measurements, require good three-component, broadband records of teleseismic earthquakes. At present, these types of studies on the seafloor are severely limited by noise on the horizontal components stemming from interaction of ocean bottom currents with the seismometer packages. It has been demonstrated that very shallow burial of the sensors is sufficient to greatly reduce noise levels (Figure 12) to the point where dozens of earthquakes each year would be useful sources for long-period horizontal signals in a typical one-year experiment instead of a handful. Shielding of the instrument might also help reduce noise.

2. Array studies with many sensors and modern interpretation techniques. Many of the most powerful observational approaches, such as body wave tomography, differential travel times of core phases, and ambient noise tomography, require arrays with many instruments and a relatively large footprint, depending on the size and the depth of the target. New full waveform techniques, such as adjoint tomography, also are most effective using arrays of receivers. If large community experiments with arrays are to be conducted, additional OBSs will have to be built.

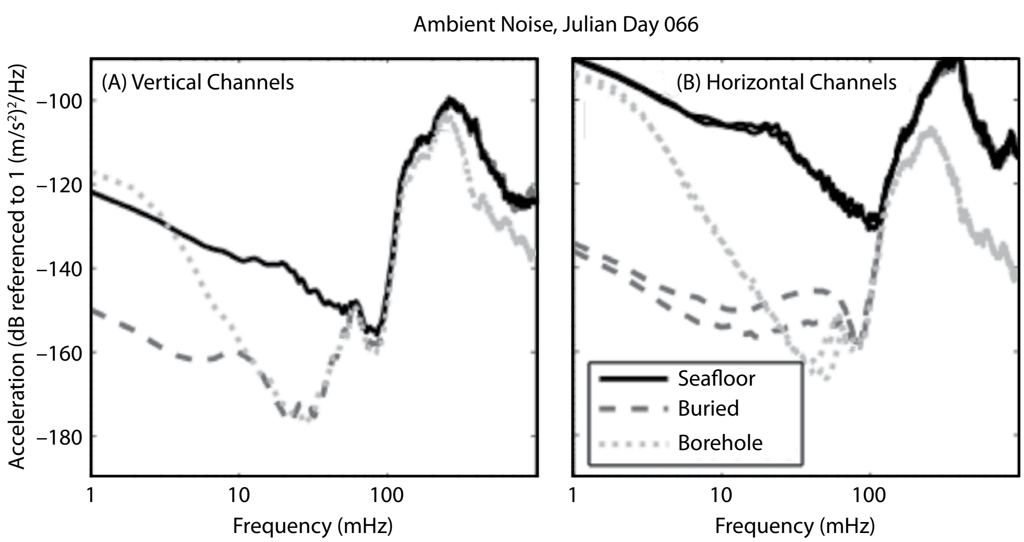

Figure 12. Noise-level comparison of seafloor, borehole, and shallow-buried seismometers from an experiment south of Hawaii. Figure courtesy of J. Collins.

Continental Margins

A rich spectrum of scientific questions on geological processes that shape our planet can be addressed at continental margins. Many of these questions concern the processes of plate-boundary dynamics, both active and ancient: plate convergence and subduction, rifting and plate divergence, and transform deformation. Others focus on the processes that underlie the fundamental continental-oceanic dichotomy that the margin characterizes, namely the processes that nucleate continental crust and lead to its growth, as well as the processes that lead to the birth of new ocean basins.

Historically, continental margins represented a significant logistical challenge for detailed study, primarily because they span the shoreline, and sedimentation buries much of the primary tectonic structure. Geologists and other Earth scientists have focused on the onshore portions, and marine geologists and geophysicists have concentrated offshore, often far offshore in the deeper ocean basins. However, to fully encompass the processes recorded at margins requires a merger of onshore and offshore observations. In part to bridge this divide, the US community developed the MARGINS (now GeoPRISMS) program to provide a mechanism for integrated work across the shoreline in a few focused tectonic environments and geographical regions. Recent OBS technology development specifically designed for deployment in continental margin settings (potentially as part of amphibious arrays) makes this an ideal time to expand margin studies to a whole suite of new scientific problems. We summarize several continental margin studies here, omitting discussion of convergent margins, as those are discussed elsewhere.

Passive Rifted Margins

The geodynamic processes responsible for continental breakup that forms new ocean basins are poorly understood. Because sediment, crust, and mantle along the margin preserve a record of these processes, improved seismic imaging along margins will permit new insights. In many places—for example, along the east coast of the United States—this process appears to have been highly magmatic, while in other places magmatic production during continental breakup is limited. At magma-rich margins, it is expected that melt generation during rifting leaves behind a depleted mantle that is stronger and more buoyant that the surrounding undepleted mantle. Furthermore, some portion of syn-rift melts might stall and freeze in the mantle lithosphere. These variations in melt production and extraction likely arise due to variations in mantle temperature, and associated changes in melt accumulation and flow. The velocity structure of mantle lithosphere beneath margins provides a means to evaluate this variation in magmatic production and extraction. Upper mantle anisotropy records pre-existing fabrics, imparted prior to rifting, and deformation during rifting. In the crust, three-dimensional *Vp* and *Vs* images of magmatic emplacement and underplating provides a means to study along-strike variability in magmatism and its possible relationship to segmentation of the resulting mid-ocean ridge. Extending the observations across strike, both onshore across failed rift basins often adjacent to the margin as well as far seaward onto oceanic crust, provides an opportunity to understand the full history of continental breakup and full range of breakup scenarios: how do the structures associated with the failed rift process compare to the successful rift? By comparing the style of accretion and deformation in the earliest oceanic crust with that produced at the associated mid-ocean ridge, we can understand the full transition to mature spreading.

Due to the cyclical nature of the Wilson cycle, passive margins also often preserve a record of the prior continent-continent collision and associated crustal growth. The mantle-lithosphere manifestation of collisional sutures observed at the surface remains understudied and poorly understood. Are sutures in the mantle sharp like those observed in the crust, or are they relatively diffuse? How are sutures preserved in the mantle over time and how do they influence subsequent tectonic events? Both lithospheric mantle and crustal structure across ancient suture zones provide important clues to the accretion process, including anisotropic fabric that records the ancient deformation. The rheological changes to the lithosphere caused by melt extraction during collision and rifting provide a mechanism for the stability of continental lithosphere long after deformation ends. This stability can be better understood through advanced imaging, both of the compositional heterogeneity in the crust and mantle lithosphere, as well as of the overlying sedimentary package that records subsequent deformation.

A number of deeper geodynamical processes may play a role in controlling the cycling of continental collision and breakup recorded at the margin. So-called edge-driven convection associated with the sharp thermal and rheological contrast across the ocean-continent lithosphere transition can produce convective patterns that stress and deform the overlying margin and, perhaps, could even be related to the melting events. Observations of the gravity field suggest that there may be "wakes" induced in mantle flow by the motion of continental plates. Improved imaging across continental margins is necessary to resolve these deeper mantle processes.

An amphibious deployment of onshore and offshore seismic instrumentation along the east coast of the United States and the Gulf of Mexico in the next several years would provide an excellent opportunity to address many of these questions. The east coast of the United States will be well instrumented by EarthScope's USArray in the 2012–2014 time frame. A coincident or subsequent offshore passive deployment, coupled with focused, passive- and active-source "flex array" style experiments, would provide the means for an unparalleled evaluation of the processes that control the breakup of continents and their subsequent evolution.

Active Rifted Margins

Active rift systems offer the opportunity to examine continental breakup, including the causes and consequences of extension and magmatism, at a relatively early stage of development. Critical questions focus on a suite of important crustal processes, including the mechanisms of strain localization, the processes that control localized and distributed modes of extension, and the role of volcanism, fluids, and sedimentation in rift evolution. Equally important questions focus on mantle processes; stresses associated with mantle flow likely drive the rifting process, and the thermal and compositional state of the mantle lithosphere establish the environment within which crustal deformation takes place. Major seismic experiments as part of the MARGINS program in the Gulf of California have produced important new insight into these questions. These analyses will presumably be continued under the GeoPRISMS program, but could be greatly enhanced by improved OBS capabilities, particularly in shallow-water environments.

One aspect of rifting that has not been covered by the MARGINS program is the process of rift initiation. What are the processes that allow a stable continent to be broken open? Active rifts within or near continental margins, including those now filled with major lake systems, provide a means to understand early stage rifting. Examples include the large lakes of East Africa, Lake Baikal, the Dead Sea, and the Walker Lane extensional zone in the western United States. These extensional systems offer an excellent opportunity to evaluate controls on segmentation in the earliest stage of rift development, and the role of magmatism in localizing rifting. They are generally seismically active, with seismicity providing a clear image of the geometry and deformation on large rift-bounding border faults, as well as smaller hanging-wall faults. Lake sediments provide a detailed record of subsidence during rift evolution.

Amphibious seismic deployments that include OBSs deployed on the lake bottom provide an excellent means to address these questions.

Transform Margins

Transform continental margins provide a unique perspective on the processes that control lithosphere-scale deformation of Earth's surface. Transform boundaries often have simple fault geometries in the crust, allowing for a relatively direct evaluation of the relationship between surface deformation and underlying mantle deformation. The California margin from Mendocino to the Borderlands (offshore San Diego) represents an excellent example of a transform boundary. In general, deformation in the mantle lithosphere across a transform boundary is diffuse; the degree of distribution, and its spatial extent, vary widely, either due to rheological differences in the crust and lithosphere, and/or differences in the underlying mantle circulation. Furthermore, subtle changes in geometry of these systems can have important geological consequences, including transitions into transtensional and/or transpressional regimes, and possible microplate capture.

Expanded seismic observations on the offshore side of transform margins will help us exploit these structures to better understand the processes controlling them. California represents a prime example. Borderland faults are seismically active, but the geometry of the faults, and their relationship to extensional and/or compressional structures along the margin, are poorly imaged due to limited offshore resolution. New observational opportunities would address this shortcoming. Nonvolcanic tremor has been recently discovered on the San Andreas, but the degree to which this behavior is present on secondary faults across the plate-boundary complex is unexplored. Instrumentation of the Borderland faults would better constrain the nature of tremor in strike-slip systems. Offshore observations would also allow for the characterization of lithospheric and asthenospheric anisotropy across the overall San Andreas system. Based on the correlation of the inferred deformation with geodetic motion observed on the surface, we can constrain the nature of forces driving mantle deformation, the rheological coupling of those forces from the asthenosphere into the mantle lithosphere, and the subsequent coupling from the mantle lithosphere into the upper crust.

The Borderlands also record a complex history of interaction along the margin—a transition from transpressional to transtensional, and the capture and rotation of the Transverse Range's microplate. The transform margin in Northern California is currently recording a transition to subduction across the Blanco transform. These transitions can be responsible for major mountain-building episodes, such as the Southern Alps on the South Island of New Zealand and the Caucuses Range in eastern Europe. These systems provide an opportunity to study the mountain-building process in its earliest stages, but they require offshore observations to fully characterize them.

Oceanic Upper Mantle, Hotspots, and Spreading Centers

Investigating the nature of convective flow in Earth's oceanic mantle and its influence on lithospheric and crustal processes requires ocean bottom seismometers. The origin(s) of volcanic hotspots and ocean islands, the convective connection of spreading centers to global-scale patterns of mantle flow, and the dynamics of tectonic, magmatic, and hydrothermal processes at spreading centers are just a few of the research topics influenced by oceanic mantle flow and upwelling.

As a consequence of oceanic mantle upwelling, approximately 85% of Earth's annual volcanic activity occurs along the global mid-ocean ridge system, thus dominating the mass and energy exchange between the solid Earth and hydrosphere. Crustal-level magmatic systems beneath spreading centers, ocean islands, and volcanic arcs drive high- and low-temperature hydrothermal activity that supports novel ecosystems whose study has altered our view of the origin of life on Earth. Active hydrothermal systems also modulate the long-term chemistry of the ocean and deposit valuable mineral resources. Tectonic processes along spreading centers and oceanic transform faults provide analogs to terrestrial tectonic processes (e.g., detachment faulting and earthquake mechanics at strike-slip boundaries) that in many cases are simpler to investigate in the marine environment.

Seismological studies using arrays of ocean bottom seismometers have made significant strides toward exploring oceanic mantle, hotspots, and ridges; however, these studies are still few in number and are generally limited in scope when compared to terrestrial studies. In the future, more ambitious, community-organized seismological experiments will rapidly advance scientific discovery as well as the exploration for mineral resources. Unlike previous decades, the rate-limiting factor for advancing ocean bottom seismology is not the technical capabilities of OBSs. Instead, what limits this field is primarily the number of available instruments and, importantly, the level of community organization required to advance mutual scientific interests.

Below we outline a few of the science opportunities for seismic studies of oceanic mantle, hotspots, and ridges, and summarize the instrumentation needs.

Oceanic Asthenosphere

The origin of the oceanic asthenosphere and what defines the lithosphere-asthenosphere boundary are outstanding issues and together were identified as one of the 10 Seismological Grand Challenges (Lay, 2009). Competing hypotheses for the origin of oceanic asthenosphere include partial melting, anomalously high temperatures as a result of plume upwelling, and the presence of water. Understanding the controls on asthenospheric rheology has important implications for the pattern and scale of convection beneath cooling lithospheric plates. Central questions include: How does the oceanic lithosphere evolve on a basin scale from ridge to trench? Why is there a lack of correlation between the thermal boundary layer and the lithosphere-asthenosphere boundary? What is the basin-scale pattern of asthenospheric flow? Does the flow couple to plate motions, and is the asthenosphere replenished by plumes? Do subducting plates advect significant volumes of asthenosphere downward? While it is generally assumed that oceanic asthenosphere responds passively to plate motions, recent studies suggest otherwise. **Figure 13** shows combined seismological and geodynamic results from the MELT experiment, which indicates that asthenosphere beneath the fast-moving Pacific Plate is moving rapidly eastward, in the opposite direction of plate motion. These results and others suggest that oceanic asthenosphere is less viscous and more dynamic than previously thought. Future studies of isotropic and anisotropic structure of oceanic mantle, particularly in the vicinity of plate boundaries and hotspots, will provide crucial constraints on how oceanic mantle and its asthenosphere respond to perturbations in driving forces and temperature anomalies. These studies, in combination with geodynamic modeling, will lead to rapid advancements in our understanding mantle rheology and thus the origin of Earth's asthenosphere and the lithosphere-asthenosphere boundary.

Ocean Island Provinces and Ridge-Hotspot Interactions

Recent advances in geophysical exploration and geochemical characterization of ocean islands and mid-ocean ridges revealed the need for both integrated and regionally focused approaches to understanding the construction of ocean island provinces and how their development influences mid-ocean ridge processes. Interdisciplinary consortia led to important advances in understanding of the processes responsible for the formation and evolution of mid-ocean ridges (Ridge 2000 program) and plate boundaries (MARGINS program). To date, no similar program has been launched for the study of ocean islands, perhaps in part because these provinces are so diverse. Nevertheless, most major ocean island systems are believed to share a hotspot origin, commonly, but not universally, ascribed to the interaction of a mantle plume with the overlying oceanic lithosphere. Among the many well-studied examples of ocean island provinces are the Galápagos, Hawaii, Tahiti, Réunion, Marquesas, Iceland, Tristan de Cunha, Azores, Canary, and Kerguelen archipelagos, and the developing plume-ridge Afar system, where decades of study have yielded important insights into the nature of these island volcanoes and the windows they provide into the geochemical evolution of Earth's interior. Yet, many questions remain unanswered, partially answered, or ambiguously related to a large-scale picture. Perhaps foremost among these questions is whether oceanic hotspots originate from a mantle plume, as opposed to some other mechanism yet to be elucidated. In addition to this overarching question, many other issues beg for explanation:

- How does hotspot upwelling interact with the lithosphere to form hotspot swells?

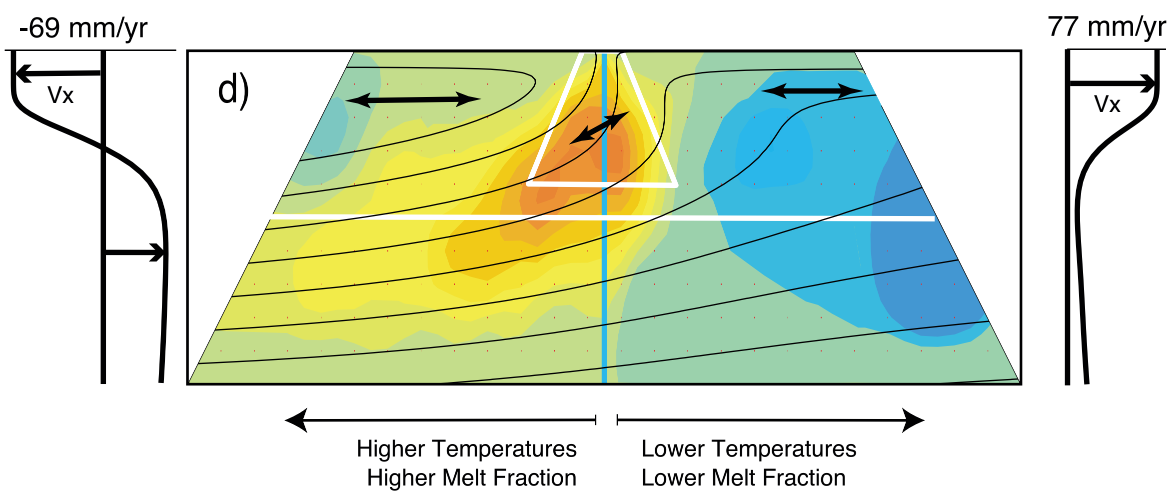

Figure 13. Numerically calculated flow lines for asymmetric spreading resulting from westward migration of the southern East Pacific Rise at 32 mm/yr, with relative viscosity increases by about two orders of magnitude between the asthenosphere and the transition zone (for details, see Toomey et al., 2002) superposed on preferred Vs model of Hammond and Toomey (2003). Two-headed black arrows indicate the orientation of seismic anisotropy (fast axis for P waves). White lines indicate boundaries between anisotropy domains. Left (right) of contoured Vs is the depth dependence of horizontal component of mantle flow velocity at the west (east) boundary, illustrating the influx of material from the western asthenosphere.

- What can geophysical methods tell us about the evolution of magmas within the lithosphere? Where is magma stored, what conduits permit its rise through the plate, and how and where does addition of magma thicken the crust?
- How do hotspots alter flow patterns near mid-ocean ridges? Are distinct channels formed connecting ridges and off-axis hotspots? What are the roles of shallow upper mantle flow and lateral melt migration, versus variations in lithospheric stress, in controlling the patterns and shapes of volcanic constructs?
- What is the nature of hotspot-lithosphere and hotspot-ridge interaction as a function of near-ridge setting or lithospheric thickness? Similarly, to what extent does hotspot upwelling and melting affect lithospheric structure and vice versa? The young, relatively thin crust and lithosphere associated with the Galápagos, compared to either Iceland or Hawaii, for example, provide opportunities to probe how variations in lithospheric thickness influence upwelling and melting.

Addressing these issues and others requires regional-scale deployments of ocean bottom seismometers and coordinated mapping and sampling of seafloor geology. Given the areal extent of many ocean island provinces and of hotspot-influenced ridges, the scale of OBS experiment required to make advances is considerable. Future integrated studies of ocean islands and hotspot-ridge interactions would benefit from community-organized, multidisciplinary experiments.

Spreading Centers

Our understanding of the formation and evolution of oceanic crust and shallow mantle at spreading centers is currently undergoing fundamental changes in perspective. Over the past decade, multidisciplinary studies undertaken at a diverse range of sites along the global mid-ocean ridge system are revealing that oceanic crust—and the processes that form it, alter it, or depend on it for their livelihood—is far more diverse than we ever thought. This diversity in structure and in the underlying processes presents major research challenges to our community. First among them is redefining our working models of crustal accretion. No longer can we view the richness and variety of oceanic crustal structure through a simple prism of fast-spreading versus slow-spreading, or Penrose (layered oceanic crust based on the study of ophiolites) versus Hess (oceanic crust is serpentinized periodotite). Instead, new working models recognize both the spatial and temporal complexity of the processes that build and alter oceanic crust and mantle. These new models reflect the coordinated efforts of geologists, physicists, chemists, and biologists to understand the links between seafloor spreading, the deep biosphere, the ocean, and the atmosphere. Second, tractability is problem. How do we begin to characterize the oceanic crust and shallow mantle—which covers nearly two-thirds of our planet's surface—if the processes that form and interact with it are more extremely diverse? Addressing this issue will require: (1) regional-scale OBS experiments that characterize structure over broad areas and thus provide context for more focused, smaller-scale studies and (2) long-term, earthquake monitoring experiments that focus on specific tectonic and volcanic/hydrothermal systems.

One area where recent progress has been made is in conceptual models of upwelling beneath mid-ocean ridges. Early hypotheses often assumed that magma supply controls segmentation, that mantle upwelling and melt delivery is symmetric about the rise axis, and that crustal accretion is complete within a kilometer or so of the spreading axis. In this overly simplistic view, all ridge-crest processes are symmetric about the rise axis and thus amenable to simple conceptual and numerical models. Recent seismic studies of the East Pacific Rise and the Gulf of California provide compelling evidence of relatively weak coupling between plate kinematics and mantle upwelling. At the Gulf of California, surface wave studies using land-based seismometers have imaged regularly spaced convective upwellings that are not centered beneath ridge segments (**Figure 14**). Beneath the East Pacific Rise, analysis of active-source data recorded by an OBS array reveals regional-scale skew and asymmetry of mantle upwelling beneath the ridge axis (**Figure 15**) as well as evidence for off-axis delivery of mantle melt and off-axis crustal accretion by intrusive magmatism. These surprising discoveries are renewing the debate over the origin and significance of spreading-center segmentation as well as the processes that control the architecture of oceanic crust and the Moho transition zone.

At slower spreading rates we now know that a profound degree of complexity and variability exists in the magmatic, tectonic, hydrothermal, and biologic processes that accompany crustal formation and evolution. In view of the apparent complexity of structure and processes at slow and ultraslow spreading rates, advancing understanding of the crust and shallow mantle formed there will require multiple efforts at conducting integrated, multidisciplinary studies that use OBS arrays for regional-scale imaging and local-scale imaging and monitoring of volcanic, tectonic, and hydrothermal processes.

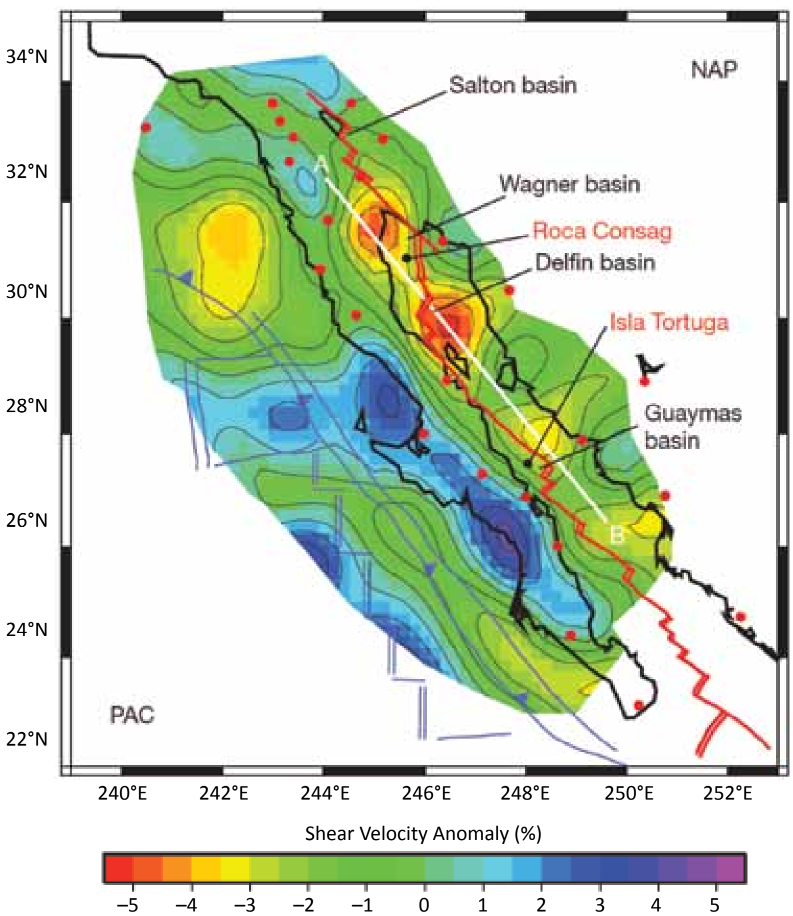

Figure 14. Shear velocity anomalies averaged over a depth of 50 to 90 km beneath the Gulf of California and Baja California region (Wang et al., 2009). Negative anomalies correspond to slow regions. The contour interval is 0.5%. The heavy black line indicates the coastline. Red lines are the current plate boundary, with double lines indicating rifts or spreading centers, and single lines indicating transform faults. Low velocity zones—which are attributed to dynamic upwelling—are not centered beneath ridge segments.

There are a number of diverse and outstanding issues that can be addressed via ocean bottom seismology, such as:

- At what depth does melting begin beneath mid-ocean ridges?
- How is melt extracted from the mantle and focused at the ridge axis?
- Is there a spreading-rate dependence to the relative importance of plate-driven vs. buoyancy-driven flow?
- How does the lithosphere extend and accrete in different melt production environments, particularly at slow- and ultraslow spreading rates where detachment faulting is prevalent?
- What is the flux of heat, mass, and volatiles out of Earth's interior to its crust and ocean, and what role does oceanic crust and exposed mantle play in modulating oceanic and atmospheric chemistry through hydrothermal and weathering processes?
- How does oceanic crust get hydrated at different spreading rates, including at the ridge axis and other seafloor features from ridge to trench? Answering this question is relevant to diverse topics, such as the role of seafloor hydrothermal and weathering processes in carbon sequestration, the mechanics of megathrusts at subduction zones, and the production of melt at arc volcanoes.

Types of Experiments and Instrumentation Needs

To address the above scientific problems requires a range of experiment types. Experiments at multiple scales will be necessary to tackle regional variations in mantle and crustal structure, to image at higher-resolution upper and lower crustal structure, and to monitor earthquakes. Nested experiments could be used at a number of different locations (e.g., ridge, hotspots) and scales, with the latter ranging from several hundreds of kilometers (e.g., ridge-hotspot interactions) to kilometers (e.g., understanding volcanic/hydrothermal systems within a ridge segment).

Nested experiments are likely to include long- and short-duration deployments of OBSs. Long-duration deployments (year or more) are necessary for both earthquake monitoring of specific targets (e.g., a volcano/hydrothermal system), and imaging experiments that use either regional and teleseismic earthquakes or ambient noise to probe mantle and crustal structure. Short-duration deployments (several weeks) are particularly useful for active-source, high-resolution imaging of structure. In terms of instrument bandwidth, both broadband and short-period OBSs are required depending on the application.

The number of broadband and short-period OBSs envisioned for any single nested-scale experiment would be 50 to 80 of each, with a typical experiment requiring a year or more of on-bottom recording time. Given this resource investment, it would be useful and cost-effective to equip these instruments with additional sensors, for example, pressure gauges and electromagnetic sensors, thereby expanding the user pool of the resulting data.

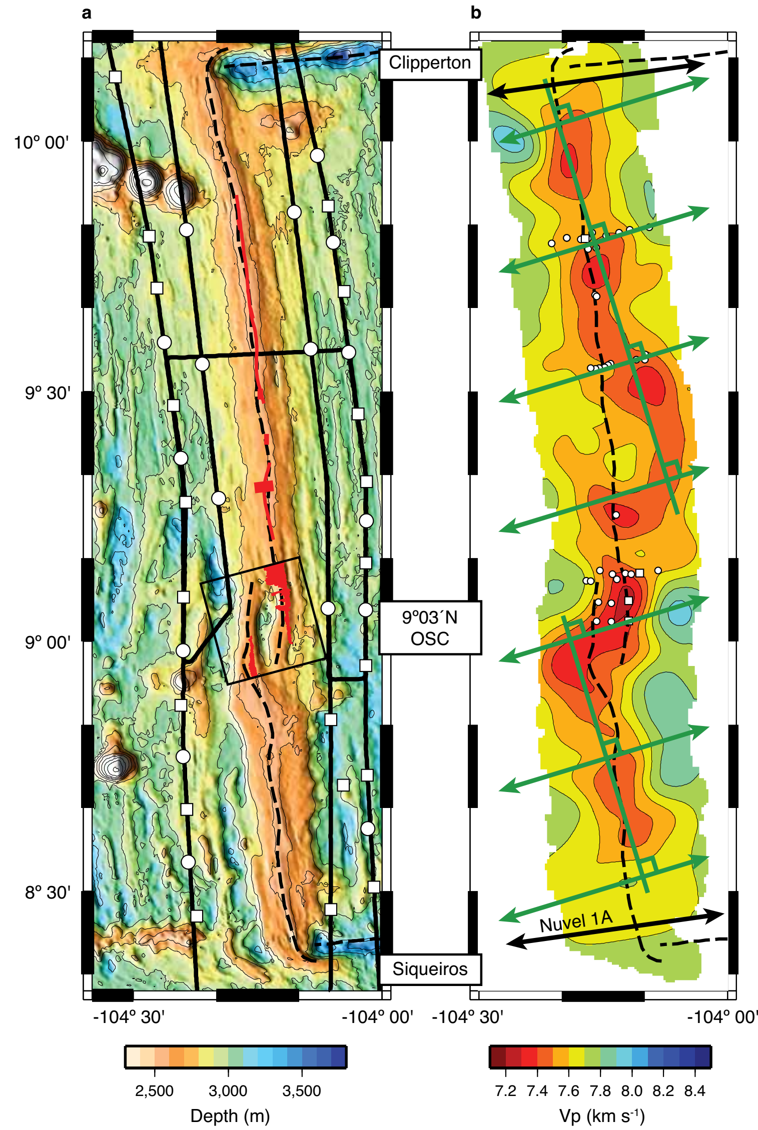

Figure 15. Location map and tomographic image of the mantle low-velocity zone (MLVZ) and orientation of mantle anisotropy beneath the East Pacific Rise near 9°N. (a) The Clipperton and Siqueiros Transform Faults bound the study area. Dashed lines show the location of the plate boundary. (b) Tomographic image of mantle P-wave velocity; contour interval is 0.1 km/s and depth of section is 9 km beneath the seafloor. Green lines with arrowheads indicate azimuth of seismic anisotropy; black lines with arrowheads indicate plate spreading direction. Green lines without arrowheads are perpendicular to seismic anisotropy and indicate locations of en echelon segments of the MLVZ.

Instrumentation to Support the Science

History of OBS Development

In the 1970s and 1980s, at least eight universities and oceanographic research institutions in the United States were developing ocean bottom seismographs, in large part with support from the Office of Naval Research (ONR). During this period, methodologies to acquire high-quality seismic data in the deep ocean were first established and seafloor seismic activity was explored. In the mid-1980s, ONR solicited designs for the first national OBS instrument pool. A consortium consisting of the Woods Hole Oceanographic Institution (WHOI), Massachusetts Institute of Technology, Scripps Institution of Oceanography (SIO), and University of Washington constructed a set of 31 ONR OBSs equipped with 1 Hz seismometers. However, as ONR support for blue-water oceanography was cut back in the 1980s and 1990s, the number of ocean bottom seismology laboratories decreased, and the national pool became dated. This contraction was occurring just as the technological developments needed to record for long time periods were being developed, potentially enabling deployments that lasted several months. Developments in compact broadband sensors also opened up ocean bottom seismology to new types of investigations.

Prior to the implementation of OBSIP, the conduct of seafloor seismic experiments generally required direct collaboration with scientists at institutions that had access to the seafloor technology. There was one major collaborative project funded by NSF's RIDGE Program—the MELT Experiment in 1995—that pooled the resources of five OBS groups and involved principal investigators from all five groups as well as outside investigators. In contrast, for terrestrial seismology, the community resource model embodied in the IRIS PASSCAL program led to development of a large number of broadband seismographs that enabled experiments by a larger community of scientists and at a scale that would never have been possible without pooling of resources. In order to develop a similar model for ocean bottom seismology, NSF sponsored workshop at the Monterey Bay Aquarium Research Institute (MBARI) on July 10 and 11, 1997, entitled *The Future of Ocean Bottom Seismology.* Thirty-seven scientists and NSF program managers attended the meeting. Robert Detrick, Fred Duennebier, Alan Levander, John Orcutt (Chair), Paul Stoffa, and Anne Trehu comprised the steering committee.

The workshop rationale was simply stated:

> *The purpose of the OBS Workshop and this report is to develop a plan for the growth in the number and quality of seafloor seismic instruments, which maximizes the likelihood of attracting new scientists to marine seismology.*

The operating environment at the time can be summarized from the report:

> *While the number of quality of instruments must increase, this is likely to be possible only through a reduction in the number of individual OBS/H groups in the US. In order to maintain the innovation in instrumentation necessary to sustain seafloor seismology through the next decade or more, any plan adopted must ensure that an adequate technical and engineering base continues to be supported. There is no guarantee that the maintenance of the current practices is a viable course of action; in fact, recent history argues strongly against this premise.*

The report made a number of important recommendations:

1. *Provide greater numbers of instruments with similar or identical characteristics*
   a. *100–200 instruments were envisioned*
2. *Preserve technical capability through funding peaks and troughs*
3. *Reduce per use costs through consolidation of expertise and increase in scale*
   a. *Fewer centers and more uniformity in design and parts*
4. *Open up OBS/H seismology to a greater user community*
   a. *The increase in the user base will occur both within and outside the NSF MG&G program*
5. *Provide a common data interface*
6. *Archive all data in a common format in a central repository*
7. *Spread the costs of OBS/H seismology to programs other than MG&G*

A competition was held for the Ocean Bottom Seismograph Instrument Pool Institutional Instrument Centers (OBSIP IICs). Lamont-Doherty Earth Observatory (LDEO) of Columbia University, Scripps Institution of Oceanography, and the Woods Hole Oceanographic Institution were selected as IICs. The seven goals have largely been met in the subsequent decade. At present, the number of available instruments is approximately 200, it has been possible to retain technical personnel in the face of an increasing number of experiments, and the size of the user community has grown, with users from NSF's Divisions of Earth Sciences (EAR) and Ocean Sciences (OCE), as well as other agencies and industry. The number of centers decreased and the deployment costs and budgets, which now include estimates for instrument replacements, are transparent. It is a simple matter to separate the science and technical costs and, as the number of technicians and engineers at sea has decreased for experiments while the numbers of available instruments increased by an order of magnitude, the costs have been contained. There are now common data interfaces largely set by the IRIS Data Management System that archives and makes data available to users.

A second workshop was held in Snowbird, Utah, in July 2000, immediately before the initial OBSIP deployments began. This *Ocean Mantle Dynamics Science Plan* workshop was led and managed by Don Forsyth and Robert Detrick and potential future experiments included:

- Intraplate swell/hotspot experiment
- Ridge-hotspot interaction—off-axis hotspot
- Ridge-hotspot interaction—on-axis hotspot
- Intraplate volcanic ridges and small-scale convection
- Active arc-backarc system
- Three-dimensionality of upwelling at a fast-spreading ridge
- Structure beneath a segmented, slow-spreading ridge
- Stratification of the oceanic lithosphere
- Deep distribution of anisotropic fabric in the oceanic mantle
- Deep structure of ocean-continent transitions
- Filling gaps in global seismic station coverage—leapfrogging regional arrays

A few of these large-scale experiments have been completed in the subsequent decade, while some are only now being funded or planned.

Current OBS Capabilities

Access to ocean-bottom seismic instrumentation is provided to the seismological community by OBSIP. NSF charged OBSIP with providing state-of-the-art ocean-bottom seismic instrumentation and at-sea technical assistance for the collection of marine seismic data by the entire US scientific community. OBSIP is a consortium of independently funded Institutional Instrument Centers, each of which provide the instruments and associated services for community use. At present, Woods Hole Oceanographic Institution (WHOI), Scripps Institution of Oceanography (SIO), and Lamont-Doherty Earth Observatory (LDEO) of Columbia University comprise the OBSIP ICCs, each funded through a separate cooperative agreement with NSF-OCE. In the near future, At the time of the workshop, it was anticipated that NSF would fund an independent OBSIP Management Office (OMO; http://www.nsf.gov/pubs/2010/nsf10570), which would be tasked with coordinating and managing OBSIP operations. That change in operations has begun, effective February 2012.

The OBSIP fleet consists of two types of instruments, delineated primarily by the type of seismometer that is used (Table 1). Short-period instruments are designed for the high-frequency seismic band, primarily for use in short-duration, active-source seismic experiments. These instruments are equipped with a three-component, 4.5 Hz seismometer, a high-frequency hydrophone, and a 24-bit A/D seismograph. The instruments are typically equipped with power to support high sample-rate (> 200 Hz) recording for 60 days or longer, sufficient to span even the longest active-source marine seismic experiments. These instruments have also proven capable of longer-term deployments focused on passive (natural) source data (e.g., local seismicity studies), recording six months or more at moderate (50–100 Hz) sample rates. At present, OBSIP operates 96 short-period instruments for community use.

Table 1.

	Short Period	Broadband
LDEO	-	30
SIO	67	41
WHOI	29	32
Total	96	103

Broadband instruments are designed to record the full spectrum of the seismic band (4.2 mHz–100 Hz) for passive experiments, using three-component sensors and a recording system capable of operating for a year or more. The seismometers generally provide good sensitivity at frequencies spanning 10 mHz–10 Hz or more (e.g., 4.2 mHz), and the instruments are also equipped with a wide-band differential pressure gauge (DPG) and/or hydrophone to provide recordings of the acoustic signal in the low-frequency ($f < 1$ Hz) or high-frequency ($f > 1$ Hz) band, respectively. The OBSs are equipped with a high-resolution (24 bit) A/D data logger with battery supply capable of 1+ year recording at 20–40 Hz. There are 101 broadband instruments presently available in the OBSIP fleet.

A number of elements are common to the OBSIP fleet, despite the independent funding and thus design for each IIC. All use a free-fall design, where the instrument is dropped over the side of the ship to descend to the seafloor under its own weight. The precise deployment location, and the effectiveness of the sensor coupling to the seafloor, cannot be controlled by the operator. Communication with each instrument is via two-way acoustic transmission from the ship, and all instruments are equipped with an electromechanical burn-wire system that allows for release of the anchor upon receipt of the appropriate acoustic command. The instruments return to the surface under their own buoyancy, and are picked up from the sea surface by ship personnel. Experiments have been conducted in freshwater while using explosive bolts for recovery. In the current fleet, glass spheres provide the buoyancy necessary for flotation, although SIO is transitioning to a new design that exploits syntactic foam. Completion of the upgrade depends upon the availability of funds. For the broadband instruments, the sensor is deployed by dropping it from an arm attached to the instrument frame, allowing it to be decoupled from the bulk of the equipment. In all cases, the overall instrument package has a fairly high profile, extending approximately a meter tall above the seafloor. As a result, the instrument is potentially susceptible to rocking by seafloor currents, as well as being snagged by trawling fishing nets. For this reason, users are strongly discouraged from placing long-term deployments in water depths of < 1000 m, and even deeper in heavily fished regions. All of the instruments are outfitted with high-precision clocks (temperature-compensated crystal oscillator [TXCO] or microprocessor-controlled crystal oscillator [MXCO]), which are synchronized with GPS time at the beginning and end of the experiment. Clock drift between these endpoints is corrected using an empirical model, with typical corrections being 2–5 ms per day. The clocks advertise accuracies in the vicinity of $3{:}10^8$ or about 1 s/yr. Data are downloaded from the instruments upon return to the ship; currently there is no capability for remote data retrieval or state-of-health evaluation.

There are also a number of differences in the instruments provided by the three IICs. The short-period instruments are supplied only by WHOI and SIO, with WHOI's design being somewhat more compact than SIO's. For the broadband instruments, all three IIC's use different seismometers: WHOI uses Guralp CMG-3T sensors, SIO uses Nanometrics Trillium seismometers (models 40 and 240; only eight of the 40s sensors remain in use and will be replaced by 240s sensors as funds become available), and LDEO uses a set of Mark Products L-4 sensors coupled to low-noise amplifiers. The digitizer systems also differ: SIO and LDEO have designed and built their own data loggers, while WHOI incorporates a Quanterra Q330. In general, these design differences reflect the choices that the IICs make in trying to minimize power consumption and still provide robust, high-resolution broadband observations from the seafloor. Design details can be found at http://www.obsip.org.

Scientists wishing to use these instruments in an NSF-funded experiment must complete an instrument-request form (http://www.obsip.org) prior to proposal submission. OBSIP provides a cost estimate for supporting the OBS work; this cost is not included in the PI's budget, but is included as supplemental information in the proposal. The budget includes the cost for preparing the instruments, expendables such as batteries, shipping, and the time for OBSIP personnel to deploy and recover the instruments. If the experiment is funded, cruises are scheduled in order of official funding, subject to restrictions imposed by instrument availability and ship scheduling. NSF provides the funding for the OBS portion of the experiment directly to the supporting IIC. The IIC is responsible for preparing, delivering, and retrieving the instruments, including providing key personnel necessary to carry out the deployment and recovery operations. The PI is responsible for overall leadership during the deployment and recovery cruises, as well as providing supporting personnel to assist with the operations. While major decision-making for the experiment rests with the PI, the OBSIP team leader retains the authority for ensuring the safety of OBSIP personnel and minimizing risk of instrument loss. Following recovery of the instruments, every effort is made to deliver data to the PI at the end of the cruise. OBSIP is tasked with delivering all clock-corrected data and associated metadata to the IRIS Data Management Center in an appropriate format (i.e., SEGY for active sources and SEED for passive sources). Data are embargoed for PI use only for up to two years following instrument recovery, at which point the data become open for community access and research.

OBSIP is funded via cooperative agreements with WHOI, SIO, and LDEO. Members receive modest annual, nonproject-specific base support to maintain/upgrade their OBS fleet; all other support is tied to funded field programs.

As of September 2010, OBSIP has supported 35 separate field programs for 104 unique PIs, involving 83 research cruises. Since the beginning of OBSIP in 2001 through 2010, there have been 1597 deployments (992 SIO, 370 WHOI, and 235 LDEO) and 59 losses. The instrument loss rate is 3.7%, which also represents the minimum bound for data loss. Figure 16 illustrates the percentage of instrument losses by year. The years 2004, 2005, and 2006 were particularly difficult. In 2004, five LDEO instruments were lost to trawling. The years 2005 and 2006 were ones in which SIO and WHOI discovered that glass balls for flotation represented a previously unknown risk for deployments near 6 km depth (eight losses). Six instruments were also lost in 2005 when an eruption occurred on the East Pacific Rise during a long-term RIDGE deployment to understand episodicity; the lost instruments were embedded in the lava flows. If these 19 instruments (losses from *force majeure*) are subtracted from the total, the loss rate drops to 2.5%.

If the deployments are restricted to active-source deployments, the instrument loss rate drops to 2%. Generally, the longer the deployment, the greater the chances are that instruments will be lost. Figure 17 represents losses associated with active-source experiments. During 2006 and 2007, no active-source ship was available; the first R/V *Langseth* experiments began in 2008. There were three active-source experiments in 2009 with no losses and no active-source experiments in 2010. There is no discernible long-term trend of increased losses with instrument pool age. At the time of the workshop, 113 broadband OBSs and 10 short-period OBSs were on the seafloor. Data loss also increases with duration of deployment; in active-source experiments, most of the data loss is due to instrument loss, but in long deployments, additional data may be lost due to failures of recording systems, premature exhaustion of battery packs, corrosion, and other problems.

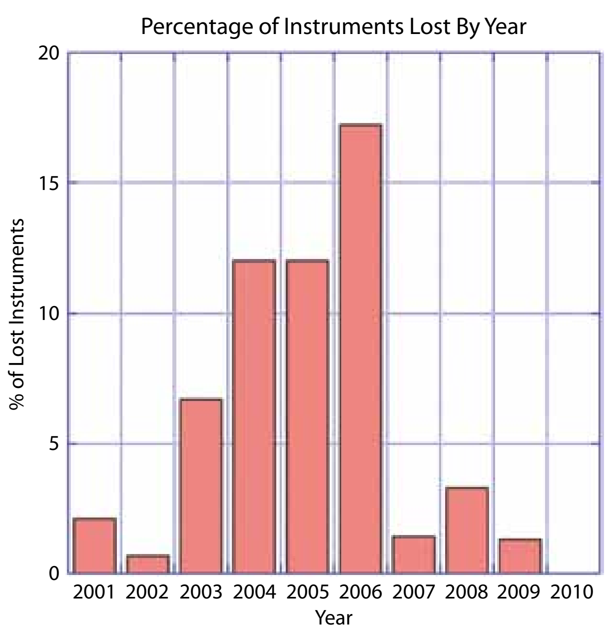

Figure 16. Percentage of instrument losses by year during OBSIP.

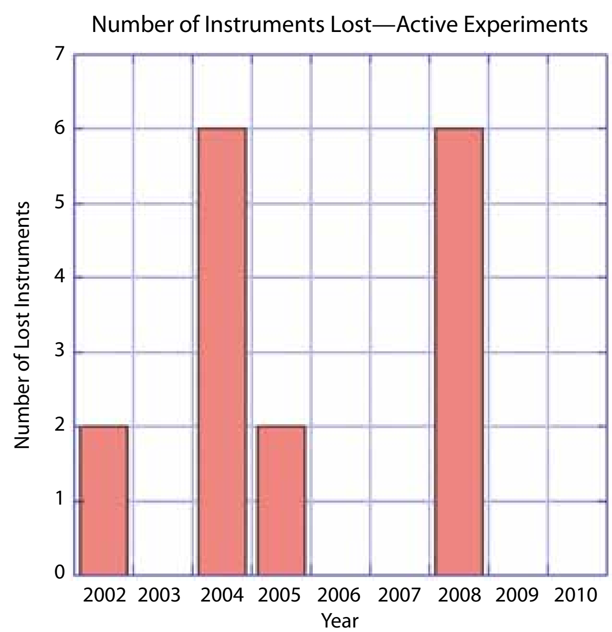

Figure 17. Instrument losses for active-source experiments during OBSIP. There was one experiment in 2003 (no losses), none in 2006–2007, and three experiments in 2009 (no losses).

Quality of Broadband Recordings: Modes, Tides, and Tsunamis

During the PLUME experiment around Hawaii, several large earthquakes occurred that excited Earth's free oscillations to levels that were recorded with excellent signal-to-noise ratios. These events provided an opportunity, given the CMG-3T and Trillium 240 deployments, to compare OBS records with those of terrestrial records. The great 28 March 2005 Sumatra event (M_w 8.6) was the only one of these events that was large enough to produce acceptable signal-to-noise ratios on horizontal components. For the remaining events, the vertical-component OBSs had extremely high signal-to-noise levels that rival those of the PLUME land installations and in many cases were superior. The Trillium 240 instruments were installed on Scripps OBSs while the CMG-3Ts were on WHOI instruments. Generally, the broader band Trillium seismometers outperformed the CMG-3Ts, which is not surprising since they have flat response to velocity to 240 s, while the CMG-3Ts are flat only to 100 s.

Recording normal modes is particularly demanding in that the high-fidelity recording must be maintained over days and even weeks without interruption or interference from other seismic events. The frequency range of greatest interest extends from 0.3–10 mHz (1 hr^{-1} = $[3600\ s]^{-1}$ = 0.27 mHz). Often ocean islands are thought of as particularly noisy compared to seismic stations on more quiet continents, although several Pacific island sites are some of the quietest in the normal mode band. The KIP site at Kipapa on Oahu is one of these.

Figure 18 plots data from the 28 March 2005 Sumatra-Andaman earthquake with M_s = 8.2 and a moment of 111 x 10^{20} Nm. During the second half of PLUME, one of the large events that was recorded was the 15 November 2006 Kuril Islands earthquake with M_s = 8.3 and a moment of 35.1 x 10^{20} Nm. Figure 19 plots the vertical components of both the WHOI CMG-3T seismometers and the Trillium 240s.

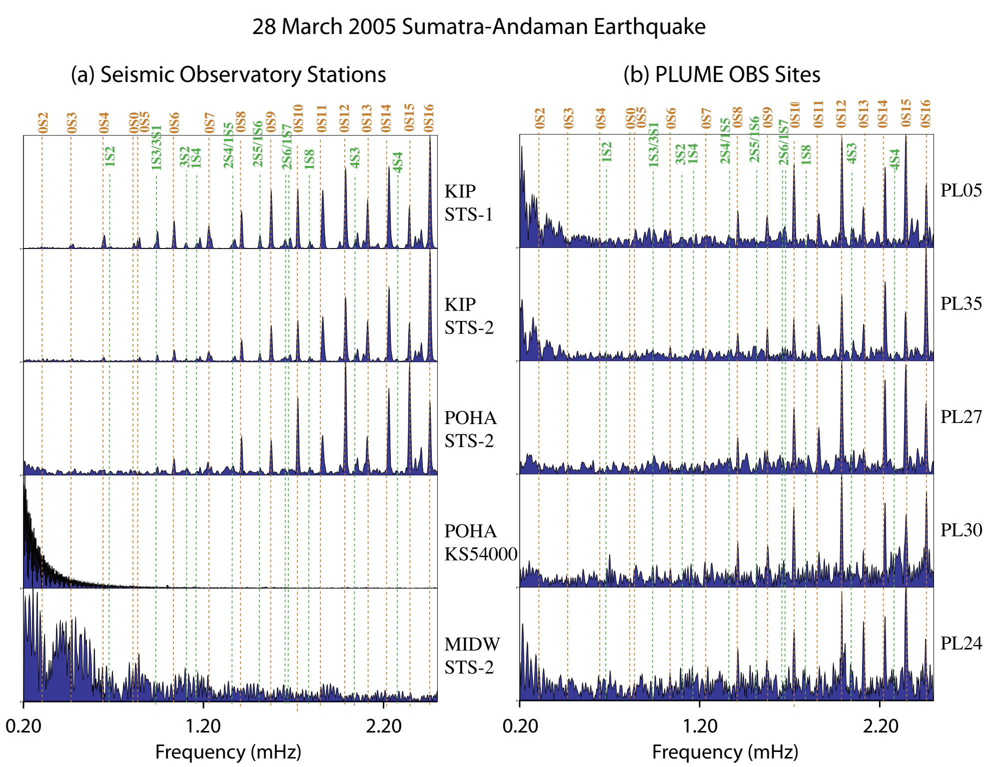

Figure 18. Vertical component spectra for the Sumatra-Adaman event using 50 hr segments beginning 90 min after the event. Modes are clear on both the STS1 and STS2 at KIP (Oahu) while at POHA (Maui), the only operating sensor (STS2) recorded free oscillations. These were not recorded at an STS2 at Midway. Five of the best WHOI CMG-3T OBS power spectra are depicted in (b). The Trillium 240s were not deployed in the first annual window of the experiment. Figure courtesy of G. Laske.

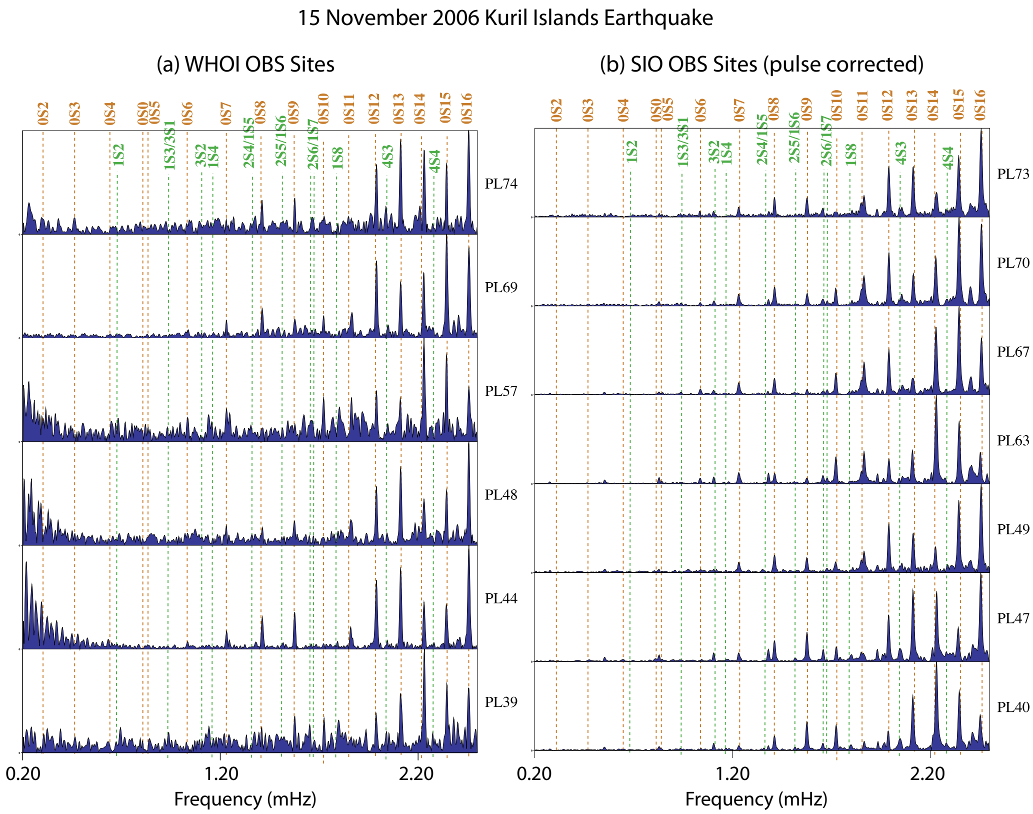

Figure 19. Vertical component spectra for the Kuril event from data recorded for 50 hours beginning 1.5 hours after the event time. (a) plots the best six CMG-3T sites whilze (b) plots seven of the eight Trillium seismometers. Figure courtesy of G. Laske.

Clearly, the broader band Trillium 240s have signal-to-noise ratios significantly higher than the ratios realized by the narrower band CMG-3Ts. For the Global Seismographic Network (GSN) stations as well as the Trillium 240 sites, the tidal mode M2 is also clearly recorded; this is not the case for the CMG-3Ts. The modes above 1 mHz are visible on both the Trillium 240s and the GSN stations, but not visible on the CMG-3Ts. The quality of the vertical very long-period signals on the Trillium 240s is comparable to the best land recordings.

Given that the Trillium 240s record M2 with considerable fidelity, the possibility arises that these records could be used as an in situ approach for providing absolute calibration of the seismometers throughout an extended experiment. Over a small area, the tides are likely to vary little and are predictable. Furthermore, compliance of the underlying lithosphere should vary little spatially.

Both the seismometers and the differential pressure gauges (DPG) can be calibrated in this way. These calibrations were performed for the DPGs by numerically estimating amplitudes over seven five-day intervals. With only these seven estimates, the error in the average calibration could be estimated to better than 10% accuracy. One of the instrument's mean calibration was 3.7% with all but one with estimates around 5%.

The Kuril Islands event also excited a small tsunami in the western Pacific. The tsunami height was 0.15 m in Guam, 0.14 m in Wake, and 0.3 m in Kwajalein. However, the tsunami height in the harbor at Crescent City, CA, was 1.5 m in height and destroyed a dock causing about $1.8 million in damages. The tsunami was recorded on DPGs in the PLUME array. The raw amplitudes are depicted in Figure 20 as well as the corrected amplitudes from M2 tide measurements discussed above.

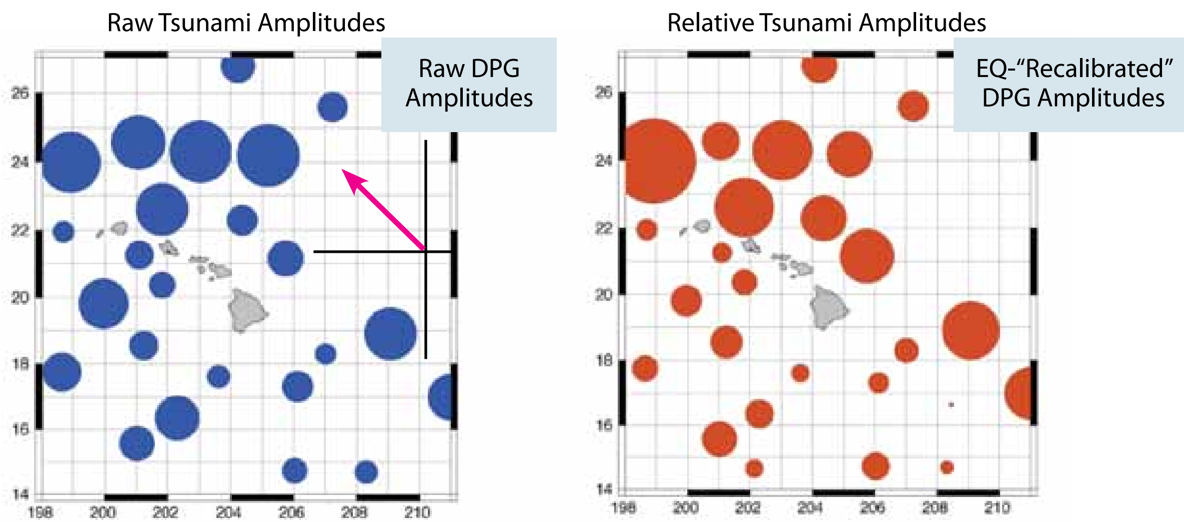

Figure 20. The largest recorded amplitudes on the differential pressure gauge (DPG) records were plotted in the left and right maps in this figure. The arrow in the left plot shows the direction from which the tsunami arrived in Hawaii. The left plot uses the raw amplitudes from the DPGs while the right plot in red portrays the amplitudes corrected using a comparison of the recorded amplitudes of M2. As noted above, the accuracy of the corrections is better than 10%. Figure courtesy of G. Laske.

This suite of recordings is the first across an array of pressure gauges; the NOAA Deep-ocean Assessment and Reporting of Tsunami (DART) buoys, which include seafloor pressure gauges, are very widely separated, have limited dynamic range and sample at slow rates. Tsunami amplitudes vary substantially across the array; the corrected amplitudes are larger to the north of the Hawaiian Island chain than to the south (Laske et al., 2009). Both the Trillium 240s and the DPGs have sufficient fidelity at long periods that they can be used effectively in tsunami studies.

Instrument Development Opportunities and Strategies for Deployment

Amphibious (Cascadia) Facility Development

At the time of the workshop, all three OBSIP IICs were in the process of designing and building new instrumentation to be used as an amphibious array, scheduled for its first deployment offshore Cascadia in 2011. A total of 60 OBSs were under construction, all equipped with Nanometrics Trillium Compact seismometers. These instruments incorporate a number of new features that will improve data quality and lower the risk of equipment loss.

Trawl Resistance. Thirty-five of the instruments are designed with smooth, convex exterior profiles to provide resistance to trawling. The 25 that LDEO is building incorporate a broad, low-profile, heavy-weight steel enclosure specifically designed to withstand a direct hit from heavy-duty trawling equipment. The heavy weight is achieved by omitting flotation, and these instruments must be deployed and recovered using a line from the ship, with the help of a remotely operated vehicle (ROV) (in the case of recovery). Although increasing ship time, this deployment strategy may prove to be lower risk than the standard free drop, because many failure points (flotation, acoustic releases) have been eliminated. This deployment strategy is limited to water depths of ~ 1000 m or less. In addition, SIO is building 15 instruments using smooth syntactic foam frames that should be less susceptible to snagging by fishing nets than the standard designs. These instruments are substantially lighter in water than the LDEO design, but they are deployed and recovered using standard free fall and acoustic means, and thus can be used in water depths extending from the shelf to 6000 m.

Current Shielding. Some of the new instruments will incorporate shielding around the sensor package in an effort to minimize rocking of the sensor by seafloor currents. For the trawl-mount instruments, the sensor is isolated beneath the convex trawl-resistant frame, which doubles as a current shield. In addition, WHOI and LDEO are building 25 deepwater instruments (15 and 10, respectively) that are similar to the design of the present fleet, with the sensor package deployed adjacent to the instrument frame. The design can be modified to incorporate a small shield surrounding the sensor ball. In the case of SIO, the sensor is deployed in a well inside the syntactic, trawl-resistant frame to limit current acting directly on the sensor. It is hoped that these designs will result in reduced long-period noise levels on the horizontal seismometer channels, which is a particular shortcoming of the existing instruments.

Absolute Pressure Gauges. The 30 instruments being built by LDEO will replace the DPG with a new Paroscientific absolute pressure gauge (APG). The DPGs have proven to be enormously successful in providing robust observations of Rayleigh waves and long-period body waves, even in cases where the seismometer fails to provide good observations. In deep ocean conditions, DPGs have resolved normal-mode oscillations, tidal oscillations, and tsunamis. The new APGs provide similar sensitivity across the same band, and extend it to lower frequency, with the capability of detecting DC vertical deformation with 1 mm precision experienced over a short time. These capabilities should permit fundamentally new observations of coseismic and post-seismic elevation changes associated with large subduction events. Furthermore, the APG has an extremely large dynamic range, which will allow it to remain on scale even in the face of wave energy in the shelf environment. Both the APGs and DPGs can be accurately calibrated.

Other New Developments

Subseafloor Burial System. The development of a subseafloor burial system for the sensor package is advocated by the scientific community. Evidence suggests that simple sensor burial can provide data quality that is comparable to seafloor borehole installations, greatly improving observations in at least deep water. WHOI has developed a burial system that has been effectively deployed in shallow-water environments, but it requires more comprehensive evaluation and testing before it can be broadly used. Japanese investigators have developed and employed a sensor burial system, but it requires an ROV for deployment and recovery, making it too expensive for most routine experiments. Other burial approaches are still in the conceptual design phase.

Three-Component Accelerometers. WHOI has built 10 instruments (with non-NSF funding) that incorporated a three-component accelerometer in addition to a broadband seismometer. These instruments have provided the first near-field, on-scale observations of seismic accelerations from several moderate-to-large submarine earthquakes. Such instrumentation would be extremely useful for near-fault, ocean bottom deployments.

Near-Shore Buoy Telemetry. LDEO and WHOI have developed and tested a prototype buoy system that can provide telemetered real-time data recovery and GPS timing for seismographs deployed in nearshore, shallow-water environments.

ROV Recovery. An ROV recovery system is being implemented for the shallow, trawl-resistant OBS developed for the Cascadia initiative, but it is also being considered more broadly for other types of deployment. Using an ROV to recover the instruments removes the dependence on two of the highest failure modes of the standard OBS system: acoustic releases and glass buoyancy. Thus, an ROV may reduce the risk of instrument loss, and more importantly, increase data recovery rates for long, passive experiments.

AUV Platforms and Autonomous Instruments. Advances in the capability of autonomous underwater vehicles (AUVs) are inspiring a broad assessment of new paradigms for instrument deployment, data retrieval, and instrument recovery. For example, the vehicle promoted at the workshop by Liquid Robotics could conceivably be used to deploy ocean bottom instruments, and/or to provide a near-surface platform for data retrieval and subsequent transmittal from instruments on the seafloor below the vehicle. Other groups are working to develop fleets of inexpensive autonomous acoustic sensors that can be distributed broadly across the ocean to provide simple arrival times of seismic events. Continued development of these ideas provides a fresh perspective on OBS science, and encourages the community to consider fundamentally new types of seismic experiments in the ocean.

Emerging Technologies

Timing

In a multiscale observatory, a common, accurate time base is essential. For single-instrument experiments, an instrument's local time may be adequate for the integration of data across an on-board suite of sensors. However, for a multiscalar, heterogeneous network or array (e.g., a collection of OBSs), it must be possible to compare samples from single sensors with other sensors located anywhere in the array while the spatial extent can extend globally. There are very good TCXOs and MCXOs that are accurate to $3{:}10^8$ or 100 ms/yr (0.27 ms/day). In many cases, this accuracy is far from sufficient.

Worcester et al. (1985) developed a solution to this problem 25 years ago. A low-power crystal oscillator is run continuously to serve as the platform's system clock. Periodically (e.g., daily) a relatively high-power rubidium atomic frequency standard is turned on for a short period, and the frequency of the low-power oscillator is compared to that of the atomic standard. The difference in frequencies is logged and used after the experiment

Figure 21. A photo of the Symmetricom SA.31m atomic clock on a chip. The dimensions are 51 mm x 51 mm x 18 mm (high). Approximately nine minutes are required to heat the oven to control temperature during which time the clock draws 14 W. The clock's accuracy, when on as an atomic clock, is $< 7 \times 10^{-10}$. The clock will operate only occasionally to discipline the TCXO.

or to compute corrections to the system clock. This approach makes it possible to maintain absolute time to a few milliseconds for a one-year period or an accuracy at least two orders of magnitude better than that from available TCXO/MCXOs.

Size and power requirements have dropped substantially over the past 25 years. Symmetricom (SA.31m) now offers a high-precision (Rb) clock with a drift of < 7 µs over a day and an accuracy in the neighborhood of $1{:}10^{10}$ or better (Figure 21). The power required is comparable to current TCXO/MCXOs. For systems, such as OBSs that cannot be referenced to accurate GPS time, this approach can be used effectively to provide timing accuracies on the order of a microsecond. EarthScope's USArray Transportable Array achieves an accuracy of about 1 µs in time (with GPS); if OBSs are to be used in a network simultaneously with the EarthScope network, comparable accuracies are essential.

John Collins (Director, WHOI Instrument Center) summarized at the workshop the time drift statistics over 344 deployments and 115 years of on-bottom recording time. He found that the mean drift was 3 ms/day with a standard deviation of 2 ms/day. The 80^{th} percentile of the observed drifts was 4 ms/day. The observed drifts are larger, in most cases, than the advertised drift rates for crystal oscillators. Substantially better timing should clearly be available using the "atomic clock on a chip" being offered by Symmetricom.

Much of the error, which accumulates between the time the OBS clock is set before deployment and following recovery almost certainly occurs as the OBS moves from room temperature on the surface to near freezing at the seafloor and, at the end of the experiment when a comparable temperature difference is realized on recovery. Worcester et al. (1985) showed this situation to be the case. While the oscillator frequency may be reasonably stable once in thermal equilibrium, the inaccuracy accumulated in launch and recovery can be quite large.

Optical Seismometry

Since the late 1960s, generally broadband seismometers have relied on the use of feedback to minimize the motion of the seismometer mass and maintain the linearity of the transducer in measuring mass position. The availability of small, inexpensive lasers, fiber optics, and interferometers has provided a new technology for measuring mass displacement.

The seismometer in Figure 22 is a schematic of a modified Streckeisen STS1 very broadband (VBB) seismometer that normally makes use of a traditional displacement transducer (e.g., LVDT or capacitance) to determine the mass' position. Feedback, based on the mass displacement is typically applied to minimize the movement of the mass and maintain linearity in the seismometer. The mass, leaf spring, and pivots for this particular vertical seismometer are the only elements of a Streckeisen STS1 in use in the schematic. There are two beam splitters, one of which sends the input signal to a retroreflector in the mass. Two interference signals are generated; polarizing optical components create a 90° phase difference between them to enable bidirectional position determination. The signals are sent by optical fibers to a processor that continuously computes the mass position based on the instantaneous intensity of each signal. The seismometer itself has no electrical connections; the effective dynamic range is quite large (the equivalent of 30 bits—there is no A/D in the system any longer) (Zumberge et al., 2010). In fact, the dynamic range is large enough that an auxiliary strong-motion accelerometer may not be necessary for making measurements close to active faults.

Figure 23 shows an STS1 seismometer converted to an iSTS1 (i.e., a purely optical version of the original Streckeisen seismometer). Tidal measurements from the optical iSTS1 are comparable to model solid Earth tides at the Piñon Flat Observatory of the Institute for Geophysics and Planetary Physics of the University of California, San Diego, and broadband seismic noise from an STS1; the iSTS1 and a Nanometrics Trillium 240 are nearly identical. However, tests at the very quiet Black Forest Observatory in Germany have demonstrated that additional improvements in the spring and hinge are needed to measure seismic noise as low as the USGS low-noise model at very low frequencies. However, the iSTS1 should be adequate to record noise levels at most oceanic sites throughout the spectrum.

Although the optical seismometer is under development for replacing existing broadband instruments on continents and the system currently is not useful in a seafloor environment, this situation is likely to change in the future with the result that very broadband seismometers will be substantially simpler than they are now.

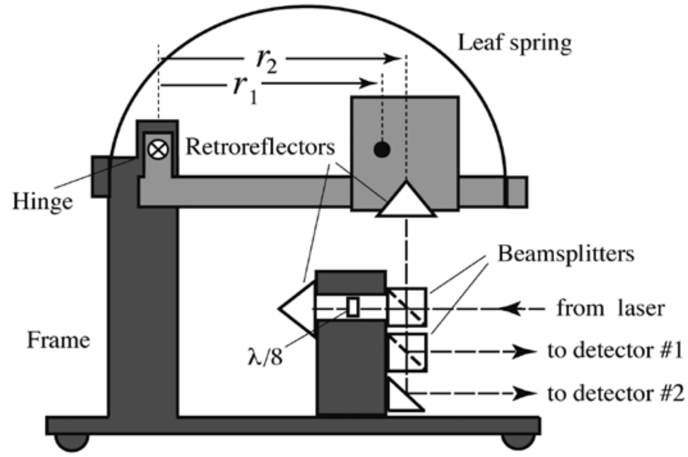

Figure 22. Illustration of the use of two laser beam splitters and a retroreflector on the mass to provide two beams to an interferometer, which measures the phase difference generated by the mass' position.

Figure 23. A modified Streckeisen STS1 seismometer, termed an iSTS1, has no electrical connections and no feedback for mass centering.

Continuing the Growth and Impact of Ocean Bottom Seismology

The community of researchers, students, and educators that routinely use data and results attained by ocean bottom experiments is in a period of significant expansion. This growth has been driven in large measure by the creation of NSF's national Ocean Bottom Seismograph Instrumentation Pool. During its decade of operations, OBSIP has benefitted from the continued development of more reliable and economical sensor and data acquisition technology. Looking toward the future, the continued growth and scientific impact of ocean bottom seismology will be driven by the rich variety of scientific and societally relevant questions that can now be addressed in Earth's ocean because of these technological developments, and by the expansion of the community of scientists who have free and ready access to ocean bottom seismic data and to the tools necessary for their interpretation. Workshop participants discussed how to facilitate continued growth of the seismological community and improved management of a growing OBSIP facility.

Expanding the Community

Earth's ocean is no longer a barrier to seismological research. Whereas in previous decades marine seismology was limited by OBS technology, and thus practiced by only a few dedicated researchers with specialized interests, recent technological advances and open access to OBS facilities is expanding the community and thus democratizing ocean bottom seismology. While this rapid expansion is ultimately driven by the science that can be achieved, there are other considerations that can contribute positively to the growth of marine seismology. Here we discuss the positive impacts of (1) enhancing free and open access to data, (2) the fostering of community experiments, and (3) the importance of looking ahead to an ambitious ocean-based observing platform for seismology.

Enhancing Free and Open Access to Data

There is an increasing recognition within the community and at NSF that data need to be shared among as many researchers and educators as possible. Putting more data and results into the hands of more researchers and educators will further strengthen and advance ocean bottom seismology and scientific discovery. Addressing this issue at the EPOBS workshop, as well as at the R/V *Langseth* workshop at Incline Village, Nevada, in March 2010, led to a consensus on three experiment modes.

PI-Driven Experiments

Proponents of PI-driven experiments are self-organized and the NSF data access policies apply. This traditional mode of operation will continue to be an important part of our community. It is anticipated that the scope and scale of these experiments is such that they can be funded through the normal proposal review process. NSF data policies currently stipulate that all data be made available to the community within two years of completing the experiment, though this moratorium may change in the future. The archiving of all OBSIP data at the IRIS Data Management Center ensures ready access for all potential users.

Open-Access Experiments

Proponents of open-access (OA) experiments are also self-organized, however, all data are immediately made available to the public. The scope and scale of these experiments are likely to be more ambitious and thus more costly than PI-driven experiments, in which case it may be more difficult to justify a moratorium on data access. By choosing an OA experiment, PIs ensure that the data have the widest possible impact on advancing research and education in a timely manner.

Open-access experiments are a relatively new development and it is anticipated that several models will be put forward by groups of PIs. For example, an OA experiment may involve separate proposals for data collection and analysis, with the former being spearheaded by the proponents and the latter being open to all investigators. Funding of an OA by NSF would thus entail a commitment to fund high-quality proposals for data analysis in order to bring the project to fruition.

Community Experiments

The community—via openly announced, NSF-supported workshops—acts as the proponent of community experiments and all data are immediately made available to the public. Community experiments (CEs) will address high-priority scientific questions that require an ambitious field program and an integrated analysis and synthesis of results. These experiments are likely to be interdisciplinary in nature and/or the data collected will be used by a broad spectrum of Earth scientists. Community workshops will define the scientific objectives and design of community experiments and put in place a management model that ensures success.

Fostering Community Experiments

Community experiments provide a new opportunity for advancing the frontiers of seismological observing and research. The community's vision of the characteristics of CEs, how to foster their development, and their organizational requirements, were developed through plenary and breakout discussions during the EPOBS workshop.

CEs are ambitious experiments that address high-priority scientific problems. The scope and scale of a CE are likely to be greater than either PI-driven or OA experiments and, thus, community buy-in is essential. Individual CEs may include a continuum of experiment modalities, for example, PI/OA/CE. A CE may have a regional focus that is essential to its scientific goals. Alternatively, it could provide an observing platform for a group of scientists who desire ocean-based data but are not defined by regional science goals. In either scenario, the objectives and scope will be defined through community workshops. It is also envisioned that CEs may have more direct coupling with terrestrial studies and/or that interdisciplinary interaction and research is essential. With proper planning and sufficient vision, a CE may be a stepping-stone to a community initiative, as defined further below.

There are several organizational requirements of CEs. A CE will be developed by workshops that define the primary science goals, the experimental design, and the management and support structure necessary to achieve the overall objectives. At present, the development of workshop proposals will rely on individual efforts. In the future, it may be desirable that the community elects a science steering committee, perhaps as part of the OBSIP Management Office, to solicit and nurture proposals for CE workshops.

CE workshops will openly develop all aspects of the project, including science objectives, experiment design, proposal preparation, experiment execution, and strategies for collaborative analysis. How a workshop achieves these objectives is likely to vary, though it is essential that significant decisions be arrived at in a manner that reflects community consensus. A successful CE will require multiple proposals, including one for data acquisition and separate proposals for data analysis.

The data acquisition proposal will motivate the science, justify the experimental design, define the experiment logistics, name a PI and/or co-PI team responsible for executing the experiment, and include a statement of data management that contains the development of metadata and data quality control. Data acquisition proposals are likely to be one to three years in duration, depending on the experimental design, and the proposal will not include funds for data analysis beyond what is necessary to develop publicly available metadata. All data, including metadata, will be made immediately available to the public via the IRIS Data Management Center. The data acquisition proposal should include a discussion of how integration of data analysis, interpretation, and synthesis will be facilitated. Advanced planning is key to a CE's success, as it will foster and encourage development of interdisciplinary teams and proposals for data analysis, integration, and synthesis.

Data analysis, integration, and synthesis proposals will be funded separately from the data acquisition proposal. Because CE data are immediately made available to the public, all data analysis proposals will be considered for review without prejudice. CEs will require well-funded programs for analysis and synthesis, including collaborative interpretation and funding of investigators. It is also anticipated that CEs will require post-experiment workshops that facilitate community collaboration and dissemination of results.

CEs have data requirements that go beyond the typical PI-driven experiment. For example, data provided by a CE should be readily usable by the community, including "arm-chair" seismologists. This constraint requires that data and metadata—for example, timing corrections, channel orientation, and instrument response functions—are routinely evaluated and uploaded to the IRIS Data Management Center in a timely manner. In addition to distributing data quickly in a useful format, a CE will need to provide a public-access cruise report. As many users of CE data will not necessarily be familiar with ocean bottom data, some assessment of data quality will be necessary. The ultimate goal of CE data archiving and distribution is that the data and metadata be as transparent to use as good-quality terrestrial data.

Improved international cooperation will directly benefit CEs by increasing the pool of available instrumentation, thus allowing more ambitious experiments. It is also anticipated that improved international cooperation could lead to new opportunities for instrument development.

The Long View: Developing Community Initiatives

Participants at the EPOBS workshop discussed the longer term, decadal-scale opportunities for ocean bottom seismology. These discussions were motivated and informed by the emerging Cascadia Initiative and also by the success of the EarthScope USArray facility, which has successfully straddled "big" and "small" science and produced a powerful net gain for seismology. Additionally, the developments discussed in the previous section—which clearly define PI, OA, and CEs as well as an emerging plan for fostering community experiments—provide a foundation on which longer-term efforts, such as community initiatives, can be leveraged.

Community initiatives are viewed as longer-duration projects (~ 5–10 years) whose umbrella encompasses all experiment modalities and that provide an observational facility that supports multifaceted research. The Earth science community, for example, created the highly successful EarthScope program using NSF's Major Research Equipment and Facilities Construction (MREFC) program. The EarthScope program supports a community resource that has resulted in the rapid growth of the Earth science seismological community, while producing both expected and unexpected advances in scientific knowledge and methods.

The advance planning required to develop a community initiative at the scale of EarthScope is considerable and argues for beginning soon so that the community can leverage the experience and success of EarthScope.

Cascadia Initiative: A Regional Science Program

The seismology community is presently gaining considerable experience on how to implement a community-wide initiative via the AARA-funded Cascadia Initiative. Due to the unique manner in which the Amphibious Array facility was funded, the larger science community has sidestepped the difficult and time-consuming issues associated with the earliest stages of developing an initiative, which include framing and motivating the science objectives and securing the essential funding that moves a project forward. The ocean and Earth science communities, instead, have proceeded directly to the equipment acquisition and experiment planning stages, much of which has been accomplished on short notice through workshops and small group conferences.

Efforts to respond to the Cascadia opportunity are awakening many to the growing science opportunities for OBS studies and to a broader user base for marine seismic data. The success and enthusiasm for collaborative efforts between the terrestrial and marine seismology communities bodes well for future interdisciplinary and interdivisional cooperation at NSF. That said, the emergence of the Cascadia Initiative has also pointed out that the marine seismological community is not yet fully organized or integrated. This topic—improved community organization and leadership—is discussed below in the context of the OBSIP Management Office.

An Ocean-Based Observing Platform for Seismology

The EPOBS workshop considered the development of a new community MREFC for seismological observations at the ocean-basin scale. An ocean-based observing system would address compelling science themes discussed in the *Seismological Grand Challenges* document (Lay, 2009), the *Ocean Mantle Dynamics Science Plan* (available at http://www.whoi.edu/science/GG/omd/omd-workshop.html) as well as during the EPOBS workshop.

Workshop participants discussed an ocean-basin-scale initiative in the context of a North Atlantic transect as one potential example of a community initiative. The centerpiece of this transect would be the collection of a high-quality data in a systematic fashion on a uniform spatial grid. This ocean-basin observing facility would allow diverse scientific studies ranging from near-surface structure and processes to deep Earth structure associated with Earth's core. Similar to EarthScope in its implementation, a North Atlantic transect would leverage PI-driven experiments similar to the USArray FlexArray component of EarthScope, that would focus on specific scientific targets within the overall transect. The observing platform provided by the North Atlantic transect could support multiple sensor modalities to increase scientific yield and engagement. Two concepts were advanced for such a transect in the Atlantic: a north-south transect from Iceland to the equatorial fracture zones, or an east-west transect from continental margin to mid-ocean ridge.

Managing Growth of the OBSIP Facility

The primary goal of OBSIP is to deliver high-quality ocean bottom seismic data to the academic community. In view of the recent and ongoing growth of ocean bottom seismology and of OBSIP, NSF identified a need for an OBSIP Management Office (OMO) that can oversee operations, ensure that the primary product is of high quality and readily usable by the seismological community, and facilitate a diverse scientific community that finds its home in all three divisions of the NSF Geosciences Directorate as well as related areas such as the Office of Polar Programs.

The NSF Program Solicitation provides a detailed description of the minimum set of tasks that the OMO will undertake:

The OBSIP Management Office (OMO) will serve as the interface between NSF/OCE, Institutional Instrument Contributors (IICs), and the OBS user community. It is anticipated that [the OMO will accomplish] the following tasks and oversight responsibilities.

- *Provide a mechanism for monitoring OBSIP IICs*
- *Subcontract IICs for OBSIP services to the broader community*
- *Provide oversight and manage funding of IICs*
- *Provide a mechanism for timely feedback by the user community regarding OBSIP performance*
- *Establish an Oversight Committee to assess the OBSIP and OMO operations*
- *Manage deployments and deployment schedules in cooperation with NSF/University-National Oceanographic Laboratory System (UNOLS)*
- *At technical level, work with IICs to ensure high and consistent data quality*
- *Maintain an OBSIP website to inform the community about OBSIP services and instruments and OBS deployment schedules and availability*
- *Ensure that OBS data are entered into the Incorporated Research Institutions for Seismology (IRIS) Data Management System in a timely fashion*
- *Provide a quarterly Activity Report and an annual progress report to NSF*
- *Submit an annual program plan to NSF with budgets for support of the management office and baseline operations of the approved IICs*

An Oversight Committee to assess the OBSIP will be established by the OMO. A charter for the Oversight Committee and the selection of its members to be selected by the OMO will be subject to approval by the cognizant NSF Program Director.

The OMO will convene the Oversight Committee at least once annually to assess the appropriateness of staffing levels and budgets, the adequacy and responsiveness of service and instrumentation to the community, whether instrument developments are adequate to meet future needs, the quality of the data, and whether each IIC continues to meet the IIC definition and criteria.

The Oversight Committee will prepare an annual report on OBSIP, including assessments of the OMO and each of the IICs. The report will be made public and will also be used by NSF in evaluating the performance and effectiveness of OBSIP.

The program solicitation defines well the management structure required to oversee operations of a growing OBSIP facility. These minimum requirements, however, do not encompass the range of tasks that the participants of the EPOBS workshop view as necessary for further development of a healthy and vibrant community.

Workshop participants strongly recommend establishing additional infrastructure that improves community organization and efficiency. Ideas considered ranged from establishing a Science Steering Committee (SSC) within the OMO to the development of a new program office for ocean bottom seismology. In either scenario, the purpose would be to facilitate interactions between scientists, organize meetings, publish literature including newsletters, and oversee an education and outreach program. The new SSC or Program Office would also be tasked with:

- Encouraging future workshop proposals that define and design Community Experiments. This task may include putting a call out for pre-proposals or letters of intents for CEs and encouraging other stakeholders to participate in the overall process for proposing and developing proposals.
- Seeking mechanisms that improve international cooperation, thereby increasing the overall pool of OBSs available for cooperative experiments.
- Encouraging instrument development for use by Community Experiments and Initiatives so that these larger experiments do not detract from the pool available to PI-driven or OA experiments. Issues related to instrument requirements and development could be addressed at an early stage, for example, when pre-proposals and letters of intent are being developed.
- Developing mechanisms for gathering additional community input on both the future direction of OBS-related science and the overall efficiency, needs, and support of the facility.

A practical way to proceed with these recommendations would be task the OMO with establishing an OBS Science Steering Committee and then building on the efforts of this committee to establish an NSF-supported program office. An OBS program office would be modeled on the successful efforts of others, for example the EarthScope, MARGINS, or IODP program offices.

Summary

The workshop identified exciting opportunities for investigating the structure and dynamics of the solid Earth, many with implications for natural hazards from earthquakes, volcanoes, and tsunamis or for evaluating the setting of petroleum resources. Seventy-one percent of Earth's surface area and most plate boundaries lie under water, so ocean bottom seismographs are essential tools for studying dynamic processes in the solid Earth, including at subduction zones, spreading ridges, transform faults, continental margins, and the deep Earth.

To carry out the needed investigations requires a variety of approaches on different scales, including:

- Principal Investigator-driven experiments by individual scientists or small groups of investigators, funded through the normal proposal review process. This traditional style of project will continue to be essential for promoting innovative approaches. Normal NSF data access policies apply, usually with open access two years after data acquisition is complete.

- Open-access experiments by self-organized groups of principal investigators, typically larger in scope and scale than PI-driven experiments. Data would be available to the entire community immediately after acquisition, but experiment design would be by the group of proponents.

- Community experiments would be high-priority, ambitious experiments of large scale developed by the community as a whole through workshops. A community experiment may be interdisciplinary or involve combined land and sea operations. Data would be available to the entire community immediately after acquisition.

- Community initiatives are longer duration (~ 5–10 years) projects that may encompass PI-driven projects, open-access experiments, and community experiments all directed toward a common goal or common area. Examples include EarthScope and the Cascadia Initiative. These large community initiatives require a degree of organization and infrastructure that extend well beyond the usual experiment, involving years of planning.

Improvements to the Ocean Bottom Seismometer Instrument Pool have been made on a continual basis, but further improvements to the fleet of instruments is needed. These improvements include:

- Doubling the number of instruments to a total of ~ 400. Currently, there is a several-year wait for access to broadband instruments after a proposal is approved, which discourages new users. Both active- and passive-source experiments are sometimes compromised by too few available OBSs. Some of these instruments might be dedicated arrays for particular purposes or community initiatives, such as the Amphibious Array or for active-source experiments using R/V *Langseth*.

- Refurbishing, replacement, and upgrading current instruments. The fleet is aging and newer technologies with improving capabilities or requiring less power are becoming available.

- Developing a system for routine burial or shielding of broadband sensors. At present, the horizontal components at long periods tend to be swamped by noise generated by interaction of bottom currents with the sensors, severely limiting the types of observational techniques that can be used in broadband seismology.

- More accurate timing. Atomic clocks on a chip can provide the improved, absolute timing needed for some types of studies, such as temporal variations in velocity within an array.

- Trawl resistance. Trawl-resistant OBSs are being developed for shallow water usage in the Cascadia Initiative/Amphibious Array, but the best approach has yet to be determined.

- Additional sensors. Taking advantage of the cost of deployment and recovery of ocean bottom instruments, other sensors could be added, such as geodetic quality pressure sensors, tilt measurements, electromagnetic sensors, heat flow measurements, and current meters.

Workshop participants strongly recommend additional infrastructure that improves community organization and efficiency. This infrastructure in the form of a science steering committee or a program office might be organized through the new OBSIP Management Office and would facilitate interactions among scientists, organize meetings, oversee education and outreach, encourage instrument development, and help develop community experiments and initiatives.

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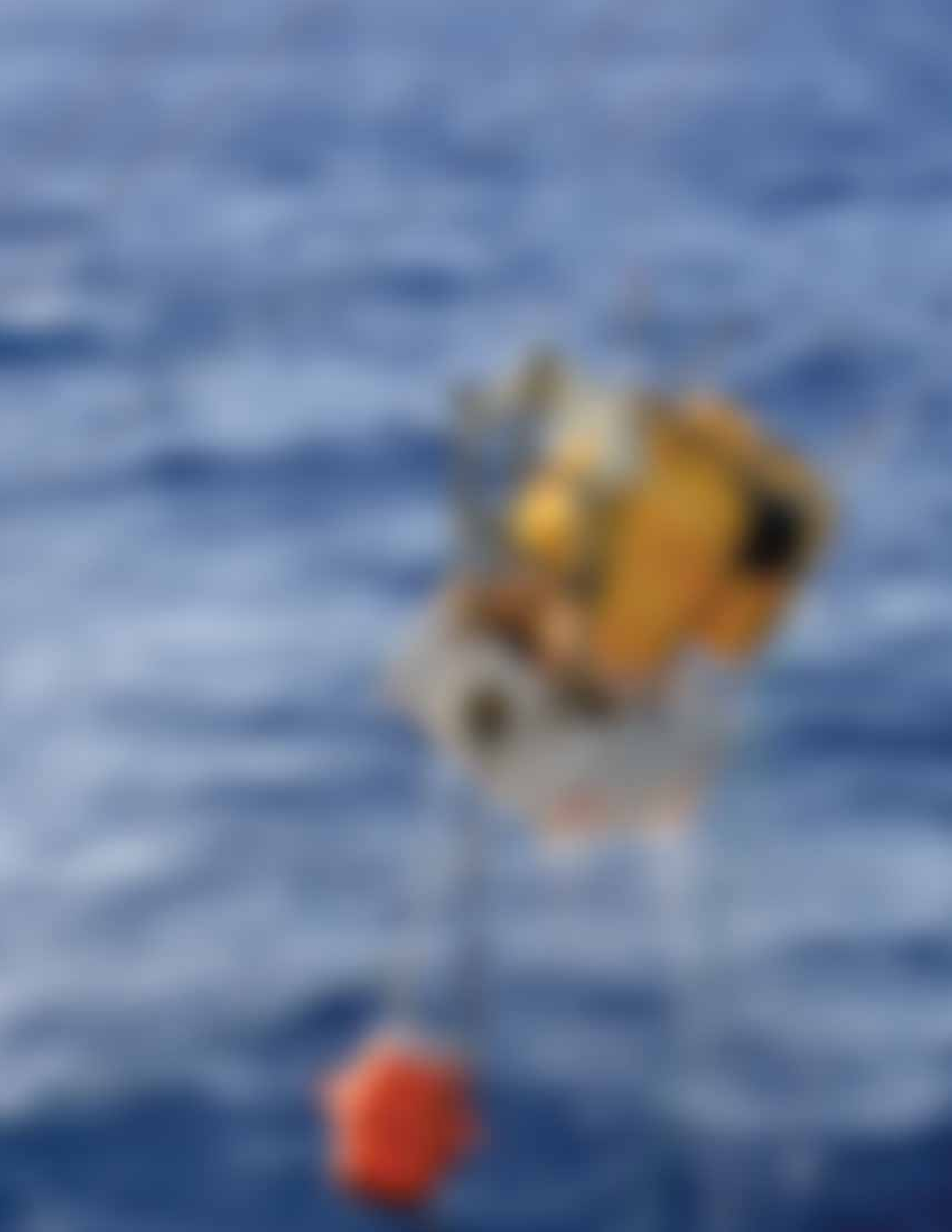

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