Oceanic Mantle Dynamics Implementation Plan: Report of a Community Workshop

Snowbird, Utah
September 18-20, 2002

Executive Summary and Workshop Recommendations

The plate tectonics revolution in the earth sciences three decades ago provided a descriptive, or kinematic model for processes at the earth's surface. The underlying mantle flow and dynamics behind this governing paradigm for the earth sciences have been far harder to elucidate. One of the greatest difficulties has been that seismic data, the primary imaging tool for the earth's interior, have been collected primarily on the continents, while most of the earth's interior lies beneath the sea floor. Recent advances in sea floor seismic instrumentation and geodynamic modeling, combined with constraints from other fields of geophysics and geochemistry, now provide unprecedented opportunities to understand the structure and circulation of the earth's mantle. The advances require an integrated, interdisciplinary approach on a large scale, far beyond the planning and resources of individual investigators. Therefore a decade-long program in Oceanic Mantle Dynamics (OMD) is needed. This program will permit major advances in our understanding of every type of tectonic setting found in the ocean basins, will yield much higher resolution global imaging of the earth's mantle, and in combination with continental USArray seismic data, will elucidate the great unanswered questions regarding the nature of the continent–ocean transition. A multidisciplinary approach centered around experiments made possible by a new generation of ocean-bottom seismometer (OBS) instrumentation could move beyond the kinematic revolution of plate tectonics towards testing and refining geodynamic models of mantle flow. The OMD program will involve scientists with a broad range of backgrounds, drawing from both the earth and ocean science communities.

The first OMD community workshop was held in Snowbird Utah September 18-20, 2002. The workshop was attended by 75 geoscientists including seismologists, petrologists, geochemists, experimentalists and modelers from both the earth and ocean sciences community. This workshop had several major goals:

- Highlight the science that can be done by focused, interdisciplinary experiments aimed at solving the outstanding geodynamical questions of the oceanic upper mantle
- Develop a plan for a "leapfrogging array" of OBS that would complement the process-oriented experiments and help improve resolution of global earth structure
- Discuss the scientific justification and technical requirements for an offshore complement to USArray
- Discuss the relationship of OMD to other major geosciences initiatives like MARGINS, RIDGE2000, IODP, CSEDI and EarthScope (including both USArray and PBO)

The workshop adopted the following recommendations and conclusions:

- *A decade-long program of focused, coordinated studies, centered around experiments made possible with a new generation of ocean bottom seismic instrumentation and incorporating constraints from petrology, geochemistry and geodynamic modeling, could make tremendous progress towards solving the outstanding questions of mantle dynamics*
- *An Ocean Mantle Dynamics (OMD) program should have three major components: (1) large, process-oriented, interdisciplinary OBS experiments and related shore-based studies to test current models of mantle circulation; (2) two leapfrogging regional arrays of OBS to fill in gaps in the global seismic network and improve resolution of global earth structure;, and (3) an offshore complement to USArray to study ocean-continent crustal and upper mantle structure*
- *An OMD program should foster an interdisciplinary approach to addressing mantle dynamics problems involving seismologists, petrologists, geochemists, geophysicists, modelers, theoreticians and experimentalists from both the ocean and earth science communities*
- *An Executive Steering Committee for an OMD program should be established immediately to continue development of the OMD program and coordinate with other major geoscience initiatives (RIDGE2000, MARGINS, EarthScope)*
- *The existing pool of broadband ocean-bottom seismometers (OBS) should be expanded, including the immediate development of OBS with buried, broadband sensors*
- *OMD should encourage the development of standardized geochemical data sets that have all analyses performed on the same samples and with availability comparable to that now existing for seismic data*
- *OMD should seek new support for an offshore complement to USArray*
- *The possibilities for international cooperation in this initiative should be fully explored*

1. Introduction

In recent years, many models of flow in the upper mantle beneath the oceans have been developed including plume upwelling and swell formation at hotspots, small-scale convection beneath plates, mantle flow and melt migration beneath fast and slow spreading centers, channelized flow from hotspots to spreading centers, convective overturn above subducting plates, asthenospheric flow associated with propagating rifts, downwelling beneath the Australian-Antarctic discordance, return flow from trenches to ridges, and flow around subducting slabs during trench rollback. These models have been based on and designed to explain observations of features at the Earth's surface, such as bathymetry, gravity and geoid fields, plate kinematics, and the composition of the melt products of mantle upwelling beneath island arcs, back-arc basins, mid-ocean ridges and intraplate volcanic centers.

Now we are entering an era when these theoretical models of flow can be tested and refined with measurements that have the power to resolve subsurface structure at critical length scales. Although much progress has been made in developing global tomographic models of mantle seismic structure, lateral resolution in the best of the these models is still on the order of 500-1000 km or more; much too long to provide the critical tests of geodynamic models that predict variations on scales of tens to hundreds of kilometers. In the last decade, PASSCAL and other similar array deployments of broadband seismometers on land have revolutionized the study of crustal and mantle processes beneath the continents. Beneath the oceans, however, high-resolution images have been obtained in only a few areas where stations can be placed on islands and/or where there are local deep earthquake sources, such as beneath Iceland or the Tonga/Fiji region.

Recent experiments such as MELT (Mantle Electromagnetic and Tomography) and LABATTS (Lau-Basin Tonga Trench Seismic) have demonstrated the feasibility of long deployments of ocean-bottom seismometers in PASSCAL-like arrays. These experiments were the first in the oceans to study earth structure using passive arrays and conventional earthquake seismology techniques such as surface and body wave tomography, shear wave splitting, and receiver function analysis. Further improvements in instrumentation planned and under development will expand the possible types and quality of observations. Now, with the establishment of a U.S. National OBS Instrumentation Pool (OBSIP) with a total of more than 100 long-duration, wide-band OBSs available for use by the broader geophysical community, there is a tremendous opportunity for dramatic progress in understanding upper mantle processes beneath the oceans. We have a new set of "eyes" with which to see the earth's interior—how can we make best use of them?

To exploit this new resource and recent advances in seismological imaging, geochemical analysis, and geodynamic modeling, a new, decade-long, Oceanic Mantle Dynamics (OMD) program has been proposed. Most outstanding problems require large, interdisciplinary experiments coordinated in time and space. The size and scope of the projects required demand coordination and broad community support and participation. Therefore a new initiative is needed to foster and implement an organized program of research focused on problems of flow in the oceanic upper mantle. The intent is that the OMD program will involve scientists with a broad range of backgrounds, drawing from both the earth and ocean science communities. In many ways, this initiative will complement EarthScope's USArray (http://www.earthscope.org) which is designed to provide unprecedented imaging of the upper mantle beneath the North American continent.

The OMD Science Plan (http://www.whoi.edu/science/GG/omd/), published in July 2000, presented an initial scientific rationale for a new initiative in oceanic mantle dynamics, outlined possible components of a decade long research program, proposed a program management structure, and estimated program costs. OMD-related field programs began in 2001 utilizing initial funding from the NSF/OCE core program. Two field programs were carried out in 2001: a study of the stratification of the oceanic lithosphere in the western North Atlantic using long-range seismic refraction profiles (J. Gaherty, D. Lizzarlde and J. Collins, co-PIs), and an interdisciplinary study combining active source and passive teleseismic experiment to investigate small-scale convection and intraplate volcanism in the southeast Pacific (D. Forsyth, C. Langmuir, R. Duncan, and S. Webb, co PIs). Two more OMD-related field programs have been funded: a MARGINS-supported active source and teleseismic experiment in the Marianas arc-back arc that will take place between 2002 and 2004; (D. Wiens and B. Taylor, co-PI) and the PLUME experiment, a passive, teleseismic study of the Hawaiian plume (G. Laske, J. Orcutt, R. Detrick, J. Collins, S. Solomon, E. Hauri, D. Bercovicci, and C. Wolfe, co-PIs) scheduled for 2003-2005. This report summarizes a workshop convened to further develop the initial plan and a more specific implementation plan with input from a broader segment of the community.

2. Workshop Goals and Organization

The first OMD community workshop was held in Snowbird Utah September 17-20, 2002. This workshop had several major goals:

- Highlight the science that can be done by focused, interdisciplinary experiments to solve outstanding geodynamical questions of the oceanic upper mantle
- Develop a plan for a "leapfrogging array" of OBS that would complement the process-oriented experiments and help improve resolution of global earth structure
- Discuss the scientific justification and technical requirements for an offshore complement to USArray
- Discuss the relationship of OMD to other major geosciences initiatives like MARGINS, RIDGE2000, IODP, CSEDI and EarthScope (including both USArray and PBO)

The workshop was attended by 75 geoscientists, including seismologists, petrologists, geochemists, experimentalists and modelers, from 38 university and research laboratories in the U.S. and overseas (see Appendix 1). The attendees were almost equally divided between earth and ocean scientists reflecting the manner in which ocean mantle dynamics problems cut across traditional disciplinary boundaries. For details on workshop structure and participants see Appendix 2. Three working groups were formed on (1) focused interdisciplinary studies of mantle circulation, (2) use of leapfrogging arrays to study global earth structure, and (3) an offshore complement to EarthScope's USArray and PBO. Their recommendations and summaries of the discussions comprise the bulk of this report.

3. Outstanding Scientific Questions in Mantle Dynamics

The theory of plate tectonics provides a conceptual framework within which the flow and composition of the oceanic mantle is related to crustal and lithospheric processes. At mid-ocean ridges, upwelling mantle undergoes decompression melting forming new oceanic crust and chemically depleting the upper mantle. Chemical and thermal heterogeneities, formed at spreading centers and altered during tens of millions of years of aging, hotspot interaction, and horizontal plate motion, are subsequently returned to the mantle by plate subduction. The subduction process not only inserts chemically differentiated material back into the mantle, but it also leads to alteration of the overlying mantle wedge resulting in melt production and arc volcanism. Hotspots erupt lavas distinct from those sampled by mid-ocean ridges or island arcs and most investigators believe they are the surface manifestation of buoyant plumes rising from the lower mantle.

Within this broad framework many fundamental questions remain regarding the pattern of flow and the dynamics of the sub-oceanic mantle. These include:

- *the scale, nature, composition and origin of mantle heterogeneities*
- *the nature, origin and distribution of mantle plumes*
- *the relationship of plate tectonics to mantle dynamics including the driving force of plate tectonics, the cooling of the thermal boundary and relationship between mantle flow and surficial tectonics*
- *the distribution of melt in the mantle and melt migration processes beneath mid-ocean ridges, at island arcs and back-arcs, and in intra-plate volcanic provinces*
- *the form and extent of small-scale convection beneath the plates*
- *the initiation and dynamics of subduction*
- *the nature of the ocean-continental transition*

- *the structure and dynamics of the transition zone between the upper and lower mantle*
- *the structure and dynamics of the lower mantle including the ultimate fate of subducting slabs, the nature and scale of the D'' heterogeneity and distribution and nature of ultra-low velocity zoness*
- *the structure of the Earth's inner core*

In the following sections, we outline the major elements of a decade-long program in Ocean Mantle Dynamics that would address these important questions, outline OMD instrumentation and resource requirements, and describe the relationship between OMD and other major ocean and earth science initiatives.

4. OMD vision

The ultimate goal of the proposed Ocean Mantle Dynamics program is to map the pattern of general circulation in the mantle associated with convection in the Earth's interior. Seismic data alone, while essential, provide static snapshots of velocity variations that can give rise to various interpretations. These data cannot unambiguously determine the circulation pattern in a time-varying, compositionally heterogeneous, anisotropic Earth. Independent information from geochemistry, petrology and other geophysical disciplines is essential. All of these observational tools are much more effective when they are coordinated and used in a hypothesis testing mode based on theoretical models of convection in the planet's interior. While much progress has already been made toward this goal through the efforts of many individual investigators and coordinated programs like CSEDI and EarthScope, a coordinated, decade-long program centered on seismological imaging in the oceans that is allied with advances in geochemistry, petrology, geophysics and geodynamical modeling will provide an effective approach for attacking the problem of determining the general pattern of circulation in the mantle. For example, three dimensional seismic structure gives information on flow directions and variations in either temperature or composition. Petrology constrains depth of melting, mantle temperature and mantle composition. Geochemistry constrains time and the origin of potential source components. Other geophysical observations add constraints on depth variations, volume, material properties, electrical conductivity, and density structure. In combination these data rule out many of the multiple hypotheses that would be permitted by one type of data alone.

There are three main elements of the OMD program discussed at Snowbird: focused, interdisciplinary investigations of individual features of the mantle circulation system; leapfrogging arrays of ocean-bottom seismometers that will systematically fill in gaps in global seismic coverage; and an offshore array of seismometers that will complement USArray, extending coverage across the continental shelves and into the adjacent ocean basins.

The focused, interdisciplinary investigations are at the heart of the OMD program because they can provide resolution of structure at a scale of tens of kms in the upper mantle; the scale necessary to understand how the convecting system interacts with the Earth's surface. The targets of investigation would include hot-spots, subduction zones, spreading centers, likely areas of small-scale convection and other individual features such as possible channels connecting mid-ocean ridges and hotspots. It is not sufficient to study one example of each of these features, since the key to understanding the dynamics of a system is to observe how it responds to perturbations, such as changes in plate boundary geometry, composition, or spreading rate. We believe that the best approach to selecting particular targets out of the many possible ridge systems, subduction zones and hotspots is for groups of investigators to compete within the normal peer review system, rather than directing the decadal program in advance through some committee structure. Coordination through an organized program, however, is essential to marshal resources for this type of study, to promote interaction and communication among disciplines, and to ensure that sufficient examples of each type of feature are studied.

The leapfrogging arrays address the need for relatively uniform, global coverage of earth structure. Current, state-of-the-art tomographic images of the upper mantle have lateral resolution on the order of 1000x1000 km in oceanic regions where there are large gaps between island stations. Leapfrogging arrays will improve spatial resolution by an order of magnitude or more. Although deployment of permanent Ocean Seismic Network and International Ocean Network stations will eventually fill in many of these gaps with individual stations, temporary deployments of arrays will provide higher spatial resolution regionally and permit the type of studies that require analysis of the detailed changes in waveform with changing epicentral distance from individual events. Coordination through an organized program is needed to direct and schedule the movement of the arrays, to spur needed instrument development, select principal investigators for each array, and to monitor the flow of data from instrument groups to the data management center.

The oceanic complement to USArray takes advantage of the unique opportunity provided by the rolling array of seismometers that will be a key component of EarthScope. The Bigfoot program of USArray is designed to provide unprecedented, uniform imaging of the continental lithosphere and asthenosphere. Without an oceanic complement, dubbed Webfoot, the resolution will decrease as the shoreline is approached, because tomographic imaging requires crossing rays and therefore stations outside the area to be imaged. In addition, Webfoot would allow tracing of deep structures associated with geological provinces into the continental shelves, imaging of stretched crust and mantle lithosphere on rifted margins, detection of the predicted convection associated with the edges of continental keels, comparison of the properties of adjacent continental and oceanic lithosphere, examination of the upper mantle under the San Andreas transform system, determination of the flow pattern around the Mendocino triple junction, and imaging of the initial stages of subduction in Cascadia and Alaska. Coordination through an organized program is essential to design and develop the needed array of instruments, supervise the deployments in coordination with EarthScope, and to monitor the flow of data from instrument groups to data management center.

In addition to this three-pronged attack on the problem of the nature of convection in the deep earth beneath the oceans, an OMD Program would play a key role in building an interdisciplinary community of scientists interested in mantle convection, helping to bridge the gap between the earth and ocean science communities, and educating the public and larger scientific community about the intriguing deep earth processes that are responsible for shaping the surface of the earth, driving plate motion, generating earthquakes and volcanoes, and cooling the earth's interior. The building of such a community leads to far greater influence for a program, and additional proposals funded through core programs that substantially extend the range of problems considered. The traditional separation between geophysical and geochemical approaches to the mantle would become far less through implementation of a joint program of study such as OMD.

5. Elements of an OMD Program

5.1 Focused Interdisciplinary Studies of Mantle Circulation

A series of focused, process-oriented, interdisciplinary studies, centered around experiments made possible with a new generation of ocean bottom seismic instrumentation and incorporating constraints from petrology, geochemistry and geodynamic modeling, hold enormous potential for revolutionizing our knowledge and understanding of the Earth's mantle. We envision 1-2 large, coordinated, interdisciplinary experiments each year that would, over the course of a decade, sample all of the major tectonic settings recognized today as important for understanding mantle circulation. What would distinguish these experiments from core-funded seismic studies would be the scale of the experiments (typically involving 50 or more OBS for a year or longer) and the involvement of seismologists, petrologists, geochemists and modelers in cooperative, integrated, interdisciplinary studies. In parallel with these major OBS field programs, OMD should support essential related shore-based laboratory and theoretical studies as well as field-based studies that address major goals of OMD. These studies will bring together a diverse cross-section of investigators from the earth and ocean sciences community who do not generally work together. An important function of a coordinated program in Ocean Mantle Dynamics will be to nurture and build this community through annual workshops and short courses. There will be significant interest from other major geoscience programs like RIDGE2000 and MARGINS in many of the process-oriented experiments discussed in the OMD Science Plan and at the workshop, and OMD should work closely with these other programs to carry out these studies.

The scientific questions that can be addressed by a decade of interdisciplinary, process-oriented experiments and related shore-based studies include:

Distribution, scale, nature and origin of mantle heterogeneities

One of the great unanswered questions about mantle structure and dynamics concerns heterogeneities in mantle chemistry, temperature, mineralogy and lithology. For example, a chemically heterogeneous mantle suggests that it is either stratified into isolated layers, and/or that mantle convection, although vigorous, does not mix the mantle efficiently. Indeed, the chemistry of lavas over sites of mantle upwelling, such as mid-ocean ridges, mid-plate ocean-island volcanoes, and island arcs, indicate significant chemical heterogeneity (Figure 1); however, the distribution of heterogeneities with depth cannot be uniquely inferred by such studies because sampling occurs on a two-dimensional surface and after uncertain melting processes that can themselves influence the final chemistry. Seismology, in particular tomography and direct wavefield imaging, can image heterogeneity with depth but only tells us about heterogeneities in seismic velocity and density, not necessarily discerning between thermal and chemical heterogeneity. Tomography however indicates that subducting slabs, inferred to be primary features in mantle circulation, extend across the entire mantle, thus giving us the clearest evidence yet for whole-mantle circulation and casting doubt on the presence of convective layering. Geodynamic modeling supports the idea that mixing can be inefficient, but there is still no consensus on models that can explain chemical heterogeneity and still be consistent with all of the first-order geophysical, geological and geochemical observations. A variety of seismic observations point to widespread, wavelength-scale heterogeneities distributed irregularly through the mantle. The nature, origin and distribution of mantle heterogeneity thus remain largely unsolved mysteries. However, it is a problem on which considerable progress can be made by focused interdisciplinary studies involving seismology with large dense arrays, petrology, mineral physics, rock rheology, geochemistry, geodynamical modeling, and electromagnetic sounding.

Seismological studies, especially with the increased coverage provided by ocean-bottom seismometer surveys, can greatly improve the resolution of the scale and distribution of mantle heterogeneities, which can then further constrain geodynamical models of the mechanisms of chemical transport, mixing and segregation in the mantle. Joint seismological, petrological, geochemical, electromagnetic and marine geophysical studies can provide invaluable information about the large-scale heterogeneities associated with the difference between, say, oceanic and continental upper mantle, or across known oceanic geochemical boundaries, or across regions with different ocean-floor subsidence rates and residual gravity anomalies. Such studies can tell us not only about the nature of these provinces and their differences, but whether seismology, electromagnetic sounding, petrology and geochemistry are influenced by the same heterogeneity. In conjunction with such studies, geochemical analyses and direct geochemical/ petrological observations of, for example, abyssal peridotites and oceanic melt compositions, can help answer the crucial question about the relation between surface chemical heterogeneity and deeper mantle heterogeneity.

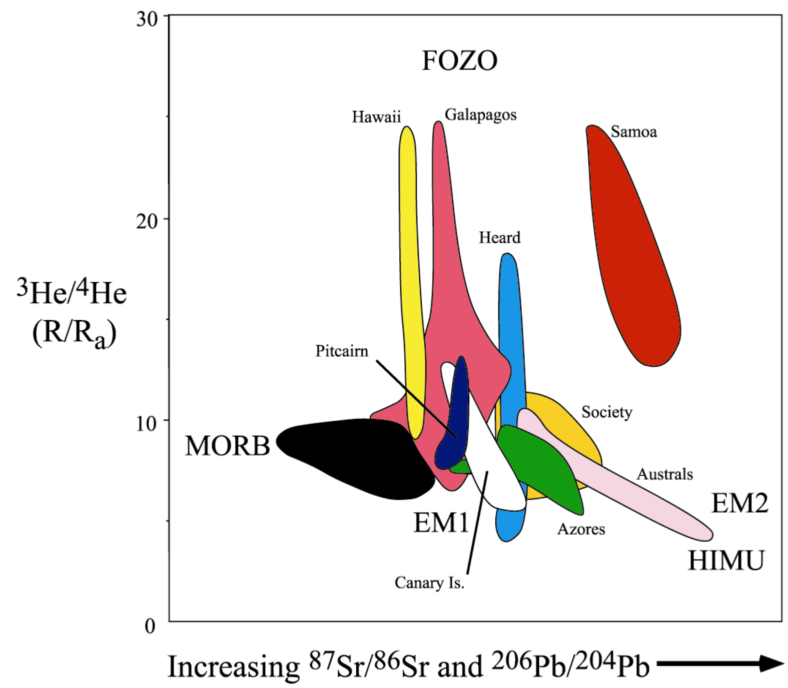

Figure 1. Two-dimensional projection of a 3-D plot of Sr, Pb and He isotopes in oceanic basalts from mid-ocean ridges and various hotspots (from van Keken et al., 2002). Results such as these indicate significant, long-lived chemical heterogeneity in the mantle. There is still no consensus on how to explain this chemical heterogeneity in light of geophysical observations (e.g. penetration of subduction slabs in to the lower mantle) that suggest whole mantle circulation..

Experimental studies of elastic properties, such as bulk sound speed, shear-wave velocity, and attenuation of mantle rocks (in particular, polyphase rocks measured at seismic frequencies) can be used to help determine the seismic resolvability of heterogeneity and what seismology may reveal about the thermal and chemical origins of mantle heterogeneity, including the role of volatiles such as water. Furthermore, experimental research on rheological properties of rocks sheared to large strain can provide important constraints on mixing and possibly segregation of phases of differing strengths.

With various measures of seismic anisotropy (e.g., shear-wave splitting), seismology also provides an important indicator of mantle fabric, and thus observations of both heterogeneities in fabric as well as directions of mantle flow. However, important calibrations of this technique and its applicability in various tectonic environments need to be carried out. For example, it is important to determine the seismically inferred fabric of the mantle where its texture is most likely to be equilibrated with the strain field. Whether shear-wave splitting and Rayleigh waves in such areas give the same anisotropy is also an important benchmark. Such studies can be done jointly with experimental studies on the sources of anisotropy (beyond simply crystallographic preferred orientation), electromagnetic soundings that can indicate fabric (due to anisotropic electrical conductivity), and numerical modeling for the dynamic generation of anisotropy by deformation-induced melt and mineral segregation as well as lattice- and melt-preferred orientation.

Seismology and high-pressure mineralogical/petrological experiments can further elucidate the bulk composition of the mantle, in particular the structure and depth variations of major chemical and mineralogical boundaries and discontinuities, such as the Moho and the various phase transitions throughout the mantle transition zone. Tomographic imaging across the transition zone, in conjunction with geodynamic modeling, can constrain the interaction of mantle phase transitions with mantle heterogeneity and flow. Direct wavefield imaging, now being widely applied to teleseismic data, can resolve heterogeneous structures at the quarter wavelength scale, equivalent to a few kilometers in the upper mantle for high frequency (1 Hz) teleseismic signals. Signal detection is possible only with large dense seismic arrays. These images when interpreted with tomography images have the possibility of providing almost "geologic" detail of the upper mantle, similar in nature but larger in scale than active source reflection images.

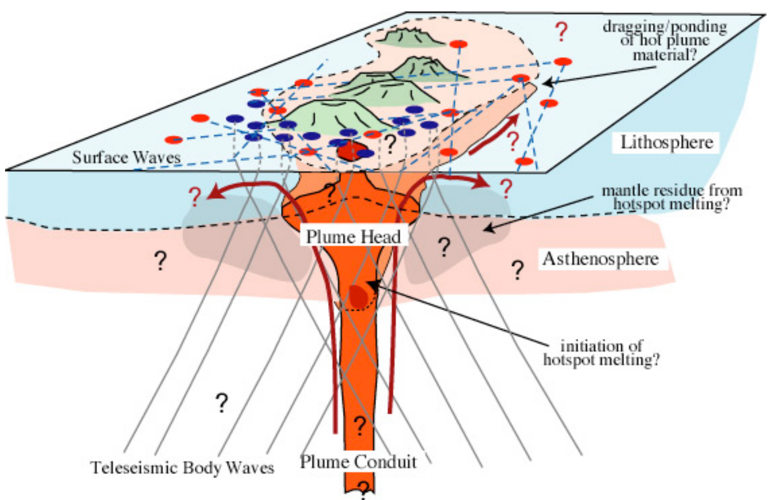

***Figure** 2. Cartoon showing elements of the plume hypothesis used to explain intraplate, lineated volcanic chains like Hawaii and an OBS array (red and blue dots) that could be used to image mantle structure beneath the Hawaiian hotspot.*

Origin of mantle plumes

Intraplate, ocean-island or "hotspot" volcanism is usually attributed to mantle plumes, that is, relatively narrow hot upwelling jets that typically rise off a heated boundary such as (presumably) the core-mantle boundary (Figure 2). Geological evidence supports the plume hypothesis in that they appear to be long-lived features that are relatively fixed in the mantle reference frame and are, thus, presumably anchored deep in the mantle. Petrological and geochemical evidence also supports this model of hotspot volcanism, both in terms of the inferred greater depth of melting leading to hotspot magmas and in terms of the distinct ocean-island basalt chemistry indicating a possibly deeper source for plumes. Geodynamical models and fluid dynamical lab experiments not only show the propensity for thermal convection and buoyant instabilities to form plumes, but also demonstrate the variety of behavior of plumes, from starting plume heads that possibly entrain surrounded material, to plume break-up from tilting under shear, to plume solitary waves that provide periodicity in volcanic output.

However, because plumes are presumably relatively narrow features (on the order of 100 km in diameter), the seismological testing of this model has been problematic. Recently some success has been obtained in imaging the Iceland plume at least within the upper mantle, both tomographically and through its effect on transition-zone phase boundaries (Figure 3). However, the presumed plume beneath Hawaii -- arguably the archetypical hotspot -- is in, a practical sense, difficult to image because the seismic array necessary to image a plume is several times the width of the Hawaiian island chain. Only with the recent advent of ocean-bottom-seismometer (OBS) technology, has it become viable to carry out a seismic survey of the Hawaiian plume by deploying a seismic array that is sufficiently larger than the Hawaiian island chain. Such an experiment is planned over the next few years. In addition, the new generation of OBS instruments also provide the potential for attacking the plume problem in many different hotspot provinces. Among the technical questions that will need to be addressed in selecting additional hotspots for study is what constitutes the best site for imaging a plume. For example, while a hotspot may have a strong volcanologic signature, it may not be ideally situated in terms of seismic sources for imaging a plume in the upper mantle.

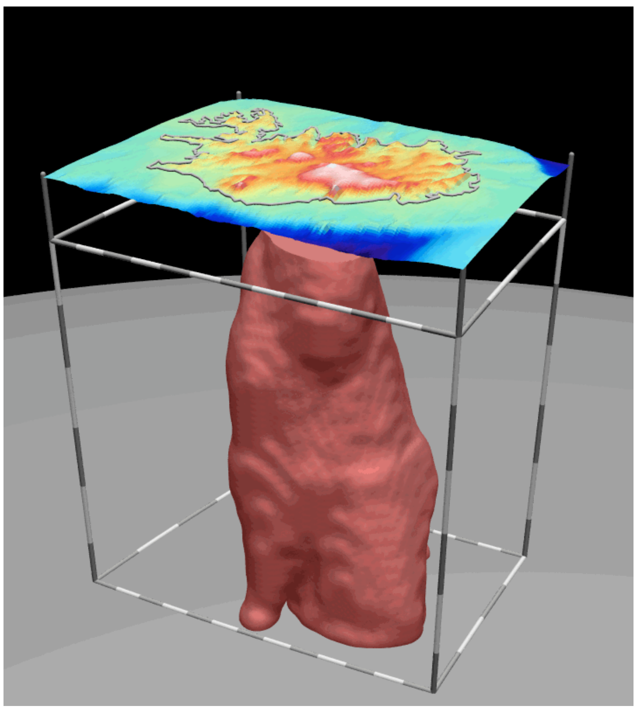

Figure 3*. S-wave tomographic image of a plume conduit in the upper mantle beneath Iceland (from Wolfe et al., 1997)*

In combination with geochemistry and geodynamical modeling, expanded OBS coverage can address the fundamental question of where plumes originate, that is, in the lower or upper mantle. Seismic coverage must be sufficient to image plumes from top down, that is, starting at its obvious location beneath the volcanic site and following the structure to its maximum depth. Similar studies can be used to address questions that have been debated over the last 10 to 20 years, such as the fate of plume material after it impinges on the lithosphere (i.e., does it pool? is it swept along by plate motion? does it thin the lithosphere? how does it flow after partial melting and, perhaps, becomes more viscous?), and the related issue of plume-ridge interactions, the archetypical case being Iceland. Other first order questions involve the physical and chemical differences between hotspots; for example multi-disciplinary experiments could be designed to study both a quintessential "hot" hotspot (whose volcanism is almost entirely caused by elevated temperatures) and a ``wet" hotspot (where volcanism is augmented by reduction in melting temperature due to a higher concentration of water). Moreover, combined field experiments could be used to examine the differences in plumes associated with hotspots beneath both young and old plates, such as Hawaii or Iceland versus Yellowstone, as well as the nature of “superswell” regions, such as that in the South Pacific. Seismological studies that resolve the finer structure of plumes, such as undulations in the plume conduit, could be performed in conjunction with petrological/rheological/volcanological studies and geodynamical modeling to constrain the cause of time-variability in hotspot volcanism (i.e., whether episodic volcanism is due to plume break-up, plume-solitary waves, or the interaction of the plume with volcanically loaded lithospheric flexure). To image the plume from the top down will require a seismic array of both considerable geographic extent, and one of relatively high density, for many models of plumes predict either thinning plumes in the middle mantle, or plumes comprising discontinuous blobs, either of which will require high resolution to image.

Relationship of plate tectonics to mantle dynamics

Although plate tectonics is widely recognized as the grand unified theory of the Earth, it is in fact still a "kinematic" theory that describes motion of the Earth's surface, but does not describe the cause for such motion. A considerable amount of work remains in understanding the driving forces of plate tectonics, its link to the thermal evolution of the planet and mantle convection, and even how plate tectonics is invariably generated from mantle dynamics.

Interdisciplinary studies, centered around OBS surveys, can elucidate many of the issues remaining in this area of study. A detailed survey of an oceanic trench environment can provide vital clues about subduction zones, in particular their thermal and chemical structure, the nature of the slab-pull force, the character of lithosphere in the slab bend, and possibly even information relevant to subduction initiation (especially if an incipient subduction zone can be found and observed). Our understanding of the so-called ridge-push force (including distributed ridge-push which involves subsidence of thickening lithosphere) can be greatly expanded by surveys of ridge thermal structure, the width of the ridge melting zones, near-ridge mantle anisotropy, and the cooling and thickening of the oceanic lithosphere away from ridges. Moreover, the role of small-scale convection in the evolution of oceanic lithosphere can be examined by joint experiments over sites of known gravity lineations. Studies of lithospheric stress, seismic anisotropy and contrasting earthquakes at different transforms can be used to infer the extent to which plates are steered by transform faults and how much they are deformed by transpressive stresses. After understanding and mapping the inferred driving forces, one can compare these to the relative motion between plates and mantle using GPS, paleomagnetics and seismic anisotropy (Figure 4).

The general relationship between plate tectonics and mantle convection can also be investigated by various joint studies. Since plates, in particular plate boundaries, are hypothesized to arise by the interaction of strongly nonlinear rheological (“shear-localizing”) mechanisms in the lithosphere with forcing from mantle convection, it is important to understand the effective rheological behavior of oceanic lithosphere and mantle. This task can be accomplished with seismic experiments, for example, probing the deep structure of transform faults and inferring lithosphere/mantle structure and fabric ahead of propagating rifts combined with laboratory studies of deformation processes that lead to ‘shear-localization’. On a smaller scale, careful ridge studies can help us understand the origin of ridge segmentation. The influence of ridge offsets, propagating rifts and rotating microplates on the deformation and fabric of the underlying mantle can be probed using seismic anisotropy.

The origin and the onset of plate tectonics can further be examined by surveying the anisotropy and thermal structure of defunct plate boundaries and the transition between tectonic provinces. The influence of continents (e.g., through their "keels") on plate motions and plate-margin deformation can be examined by transect surveys across continental margins. The deformation behavior of oceanic vs. continental lithosphere can also be examined further by an investigation of seismic cycles and stress triggering, in addition to geodetic measurements (GPS).

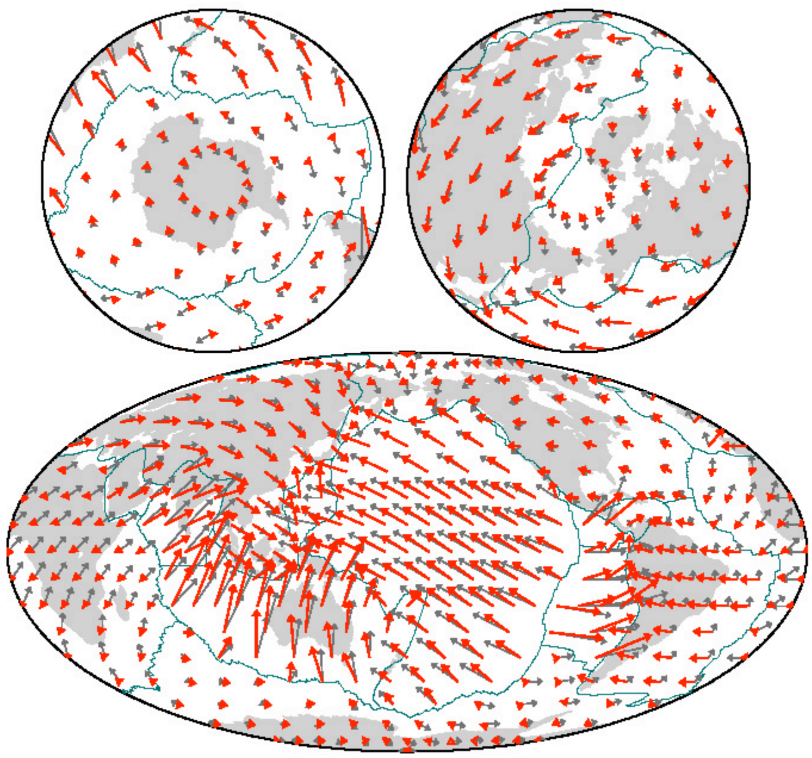

Figure 4. *Predicted plate velocities (red thick arrows) based on an S-wave mantle tomography model compared with observed NUVEL-1 plate motions (gray, thin vectors). The agreement between observed and predicted plate motions can be used to constrain the relative importance of various plate driving forces. Improved mantle tomography models from seafloor-based studies can lead to a better understanding of the relationship between mantle convection and plate tectonics. From Becker and O'Connell (2001)*

Subduction zones and fate of slabs

Subducting slabs are, through the "slab-pull" force, generally considered a primary engine of plate tectonics. Although slabs are well delineated at least in the upper mantle by the distribution of deep earthquakes (the Wadati-Benioff zone) and tomographic images, many issues, such as initiation of subduction zones, the internal structure of the subducting and deforming slab, and the fate of slabs in the deeper mantle, are still poorly understood. Thus, much remains to be learned from detailed seismic, petrological, geochemical and electromagnetic surveys of various oceanic subduction zones, from fore-arc bulges, across the trench and arc regions, and through back-arc basins. Seismic tomography, direct imaging, and anisotropy can, in conjunction with geodynamic modeling and petrology/geochemistry, continue to inform us as to the flow and temperature structure of subduction zones and slabs, why slabs either stall or penetrate the 660 km phase change, of the dynamics of back-arc spreading centers, mantle wedges and their relation to island arcs, and to the processes leading to trench and slab rollback (Figure 5). The understanding of seismic properties of slabs and trench environments should also be augmented by experimental studies on the causes of deformation-induced seismic anisotropy and the elastic and plastic properties of slab material, including measurements of the effects of temperature, melt and composition on viscosity structure and seismic velocities in slabs and mantle wedges. The petrologic processes leading to arc volcanism (slab melting or mantle-wedge wetting) also can be elucidated through surveys that compare, for example, hot and cold mantle wedges. Enigmatic behavior of slabs in the deep mantle, such as the dual Wadati-Benioff zones and the loss of seismicity below 700 km, could be investigated through joint seismological, experimental/rheological and geodynamic studies of deep-slabs.

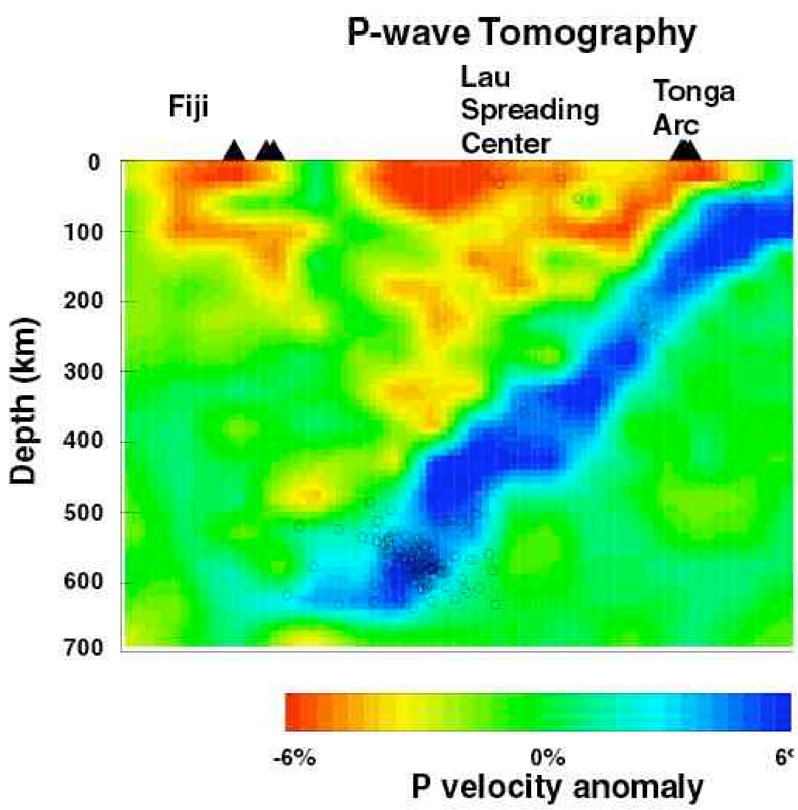

***Figure 5**. Seismic tomographic image of P-wave velocity anomalies across the Tonga arc and Lau backarc from the 1994 LABATTS experiment (Zhao et al., 1997). Fast velocity anomalies (in blue) delineate the subducting slab; slow anomalies (in yellow, red) are present beneath the Tonga volcanic arc and Lau spreading center*

Finally (and as mentioned above) possible surveys of an incipient subduction zone (such as the Macquarie Ridge, or the subduction reversal suggested for the Banda Arc) would be extremely useful for helping us understand the processes associated with subduction initiation.

These would necessarily be augmented by experimental and theoretical studies of rheological properties of slab material, in particular as it passes through the trench.

Melt distribution and dynamics

Magmatism at mid-ocean ridges, intraplate hotspots, and back-arc systems represent the products of mantle melting. However, melting and melt-migration are themselves complicated processes that leave their own signature on the resulting magma. The depth and extent of melting and differing source compositions all lead to different possible evolutionary paths that melted material can take before reaching the surface. Therefore, in order to decipher what surface magmatism tells us about the mantle at depths, it is important to understand the various aspects of melting and melt transport in the mantle.

Seismological, petrological/geochemical, rheological and geodynamical studies can, especially with enhanced OBS coverage, greatly expand our knowledge of melt distribution and migration processes in the mantle and answer some fundamental questions such as whether or not there is melt everywhere in the low-velocity zone. Field measurements of seismic attenuation in areas of anomalous anisotropy can be used to test the hypothesis that such fabric is melt-induced. These measurements can be augmented by laboratory studies on attenuation (i.e., the quality factor "Q") at seismic frequencies and deformation to large strain in samples with and without melt.

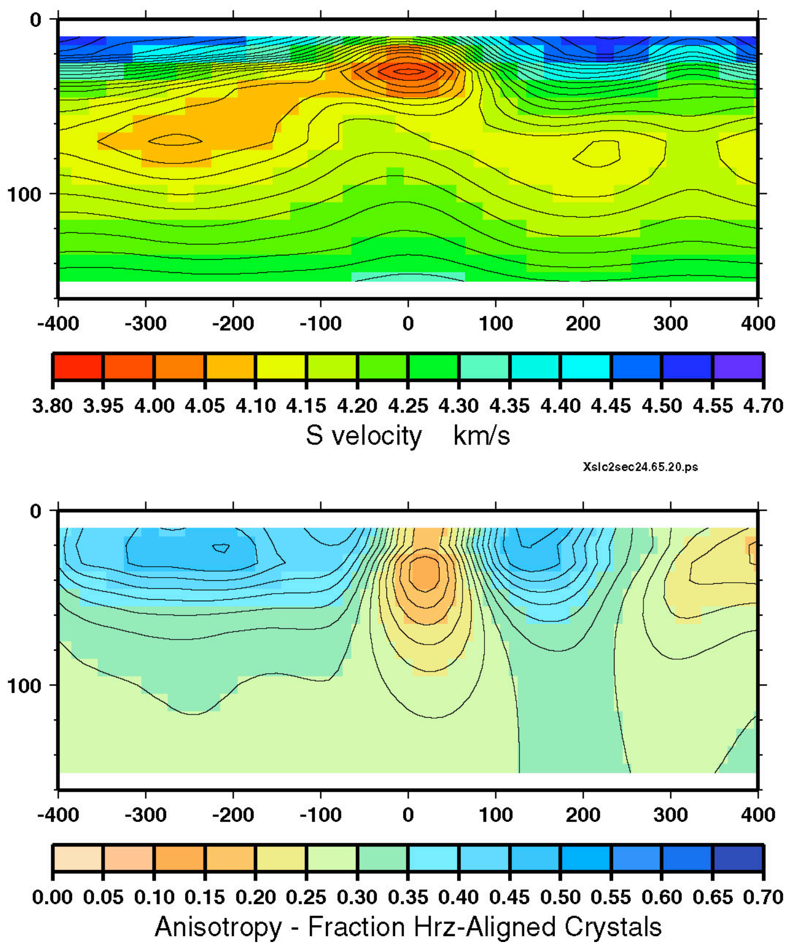

***Figure 6**. Cross-section through the East Pacific Rise in the MELT area showing shear velocity (top) and alignment of olivine crystals (bottom) based on inversion of Rayleigh waves. Note evidence for asymmetric mantle flow and melt distribution beneath the EPR (from Toomey et al, 2002)*

Although there has been considerable work on mid-ocean ridges in the last decade, our understanding of mantle flow, melting and melt-focusing at ridges remains far from complete. Questions remain about the influence of, for example, spreading rate, ridge-offset structure and mantle temperature on the melting regime beneath ridges. Seismic, petrological and marine geophysical (bathymetry/ gravity/magnetics) studies of the three-dimensional melt structures in ultra-slow spreading centers (especially, magmatic centers surrounded by amagmatic regions) would greatly elucidate some of the more complex structures of ridge environments.

Investigations of melting associated with intraplate volcanism and anomalous near-ridge volcanism are also important to carry out in conjunction with studies of (or search for) mantle plumes. For example, the origin of discrete volcanoes, whether controlled by plume dynamics or the interaction of melt percolation with lithospheric stress, is still a controversial topic. Moreover, not all intraplate volcanoes are due to plumes, such as those with non-age-progressive island chains. Thus, it is important to understand anomalous melting away from known hotspots using combinations of petrology, geodynamics, seismic attenuation and tomography, as well as electrical conductivity.

The cause for large igneous provinces is still a hotly debated issue; even the favorite 'starting plume-head' model is not universally supported by all observations, in particular in the Pacific where the marine analogs of large igneous provinces, oceanic plateaus, are not easily associated with hotspot tracks. Finally, one of the greatest issues in mantle dynamics, the history and dynamics of crustal production (both oceanic and continental), remains an extremely fruitful area of research with relevance to the evolution and chemistry of the mantle. New seismological surveys run jointly with geochemical analyses (e.g., uranium-series work complementing seismic studies of crustal thickness) would shed considerable light on these issues.

In summary, an interdisciplinary ocean mantle dynamics program, centering around new ocean-bottom seismometer surveys, holds enormous potential for revolutionizing our knowledge and understanding of the Earth's mantle.

5.2 Investigation of Global Mantle Structure and Circulation with Leapfrogging Arrays

A full understanding of the dynamics of the deep earth requires global coverage of intermediate-scale (hundreds of kilometers) structure from upper mantle to core. The distribution of land seismographic stations achieves the required density in some regions only and the distribution of seismic stations is most sparse in the oceans. Indeed, coverage in the oceans, currently confined to oceanic islands and three permanent seafloor stations , does not allow adequate determination of global structure at the longest wavelengths (thousands of kilometers). Ocean coverage will improve considerably when the ~20-30 stations of the Ocean Seismic Network (OSN) and International Ocean Network (ION) are deployed (Figure 7). However, even when fully deployed, OSN/ION, with a station spacing of about 2,000 km, will not allow the resolution of even intermediate-scale structure in the oceans. Rather than wait for the deployment of permanent seafloor stations with OSN/ION station spacing or better, substantial progress toward the determination of intermediate-scale structure can be made in the immediate future by the temporary deployment of "leapfrogging" arrays of ocean-floor seismographic stations. As the name suggests, these arrays would, over time, be moved from region to region, and ultimately would occupy a large swath of the ocean floor.

We envision operating simultaneously two arrays of 25 stations each that would be deployed over an area of about 1000 x 1000 km. A uniform distribution of stations, which may or may not be the preferred geometry, would then result in a spacing of 250 km. Each array will consist of three-component buried broadband sensors capable of recording high quality data up to at least 100 sec period, as well as auxiliary instruments (long-period pressure sensors, current- meters) that will help remove correlated background noise from the seismic signals. The arrays will be deployed in each 1000 x 1000 km box for a period of one year. This deployment time is a compromise between the need to record a sufficient number of high-quality events at a particular location and the need to provide as much coverage of the ocean floor as possible over the anticipated 10-year life of the OMD program. While on scientific grounds alone, it might be argued that the initial deployment of the leapfrogging arrays should take place in the Southern Ocean, we propose that the northeastern Pacific and North Atlantic are two areas where much scientific progress could be made, and where weather and cruise logistics (availability of research vessels, relatively short transit times) would make initial deployment more manageable. The two arrays would then migrate southward and eventually into the Southern and Indian oceans (Figure 7). As discussed in detail below, the equatorial Pacific is a crucial area for the understanding of the dynamics underlying the Pacific Plate, and the central Atlantic is the optimum location on the globe to measure core phases.

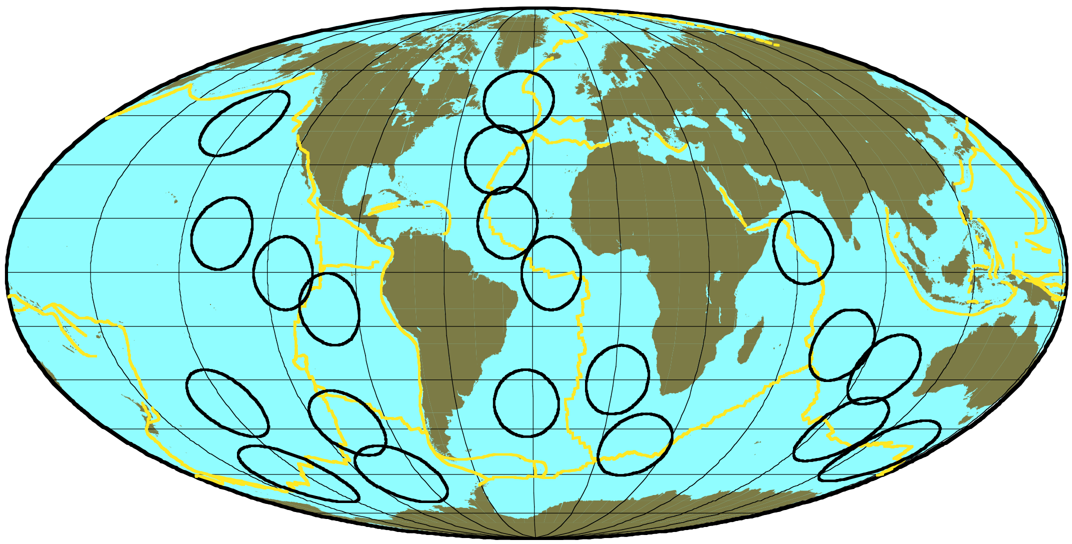

***Figure** 7. Map showing gaps in Global Seismic Network coverage (outlined in black) that would be occupied by OMD leapfrogging arrays. Some of these sites may eventually be monitored by permanent stations of the Ocean Seismic Network. Sites in the northeastern and equatorial Pacific are highest priority for understanding mantle dynamics beneath the Pacific plate, while sites in the North Atlantic are optimal for studying core phases. An additional site in the Arctic (not shown) would fill in a large gap and provide control on inner core anisotropy.*

Although the backbone of the arrays is expected to be relatively standard, some fraction of the arrays could be flexible and the exact location of the overall array within a gap could be shifted (Figure 8). This flexibility would allow each array deployment to be optimized to image a regional tectonic target or to focus on a particular deep structure, like the nature of the core-mantle boundary, by using a particular earthquake zone as a source region. We envision having individual PIs (principal investigators) for each array deployment who would be responsible for designing that particular array, overseeing the deployment process (from a scientific, not technical standpoint), and initial quality assessment of the returned data, including determination of instrument orientations. There would be no need for the PI to have previous sea-going experience, which would help broaden the community involved in using ocean-bottom seismometers. Each PI would be selected by the OMD steering committee in a competitive process based on their proposal for the design of the particular array. The PIs would not have priority or exclusive use of the data, as the data would be immediately available to any interested investigator through the IRIS Data Management Center (DMC). However, the PIs would have the advantage of having the array optimized for their particular interests, within the overall guidelines established by OMD.

The science questions that can be addressed by the deployment of two leapfrogging arrays over a 10-year period fall into two broad classes. One class of problems is focused on lithospheric and upper mantle structure beneath the array. Another set of questions and scientific goals concerns the lower mantle and the core. These deeper targets may be best sampled in regions at substantial lateral distance from the array. We have thus chosen to group these questions roughly in order of increasing depth in the earth.

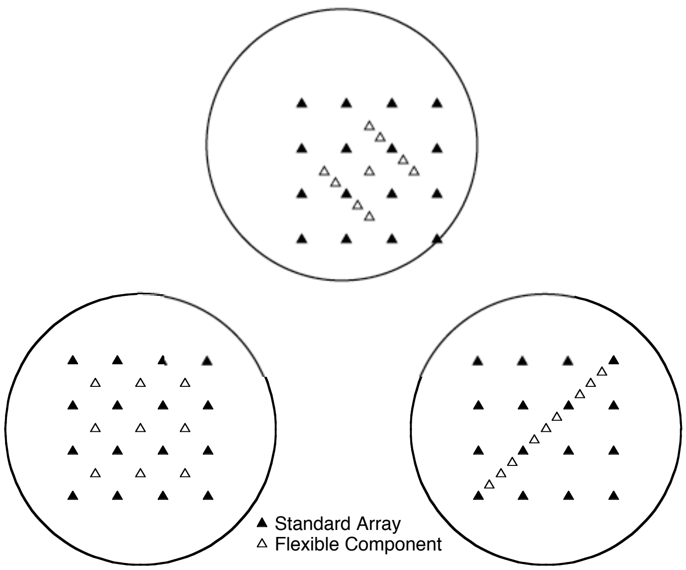

Figure 8. *Schematic potential designs of leapfrogging arrays. Location of 2000-km-diameter target circles and minimum, standard array designs would be designated by an OMD committee or workshop, but principal investigators for each deployment would have the flexibility to move the 1000x1000 km array within the target area and to design the flexible component to maximize scientific return.*

Thermal structure and dynamics of oceanic lithosphere/asthenosphere

To first order, many important predictions of plate tectonic theory have long been verified through seismological observations in the ocean, e.g. the thickening of the oceanic lithosphere with age as inferred from surface-wave dispersion data, and the alignment of the fast axis of azimuthal anisotropy perpendicular to the mid-ocean ridge system. However, some recent observations, mostly made possible by the increased quality of broadband seismic data collected on land in the last 10 years through the efforts of the Global Seismic Network, indicate significant and puzzling departures from the simple plate tectonic model. This is particularly notable in the fast-spreading Pacific Ocean. For example, the fast axis of azimuthal anisotropy changes direction significantly at some distance from the ridge in the central Pacific. This may somehow be related to secondary convection in the upper mantle, which was proposed originally to explain the departure of subsidence of the seafloor from the square root of age relationship expected for a cooling half-space. The length-scale of this convection would be on the order of several hundred kilometers, and it is not clear even now whether the convection cells are aligned perpendicular or parallel to the ridge system. The thickening with age of the oceanic lithosphere is itself being questioned. It is not equally visible in Rayleigh and Love fundamental-mode surface-wave data, as the signal is complicated by the presence of significant transverse isotropy, with horizontally polarized S waves traveling faster than vertically polarized ones, with the largest polarization anisotropy in the central Pacific (Figure 9). Also, there appears to be significant variability in age-dependent thickening of the lithosphere from ocean to ocean, which may be related to differing spreading rates, but also to the available lateral resolution: for example, a transverse anisotropy anomaly is visible in the western Indian Ocean in some models but not others.

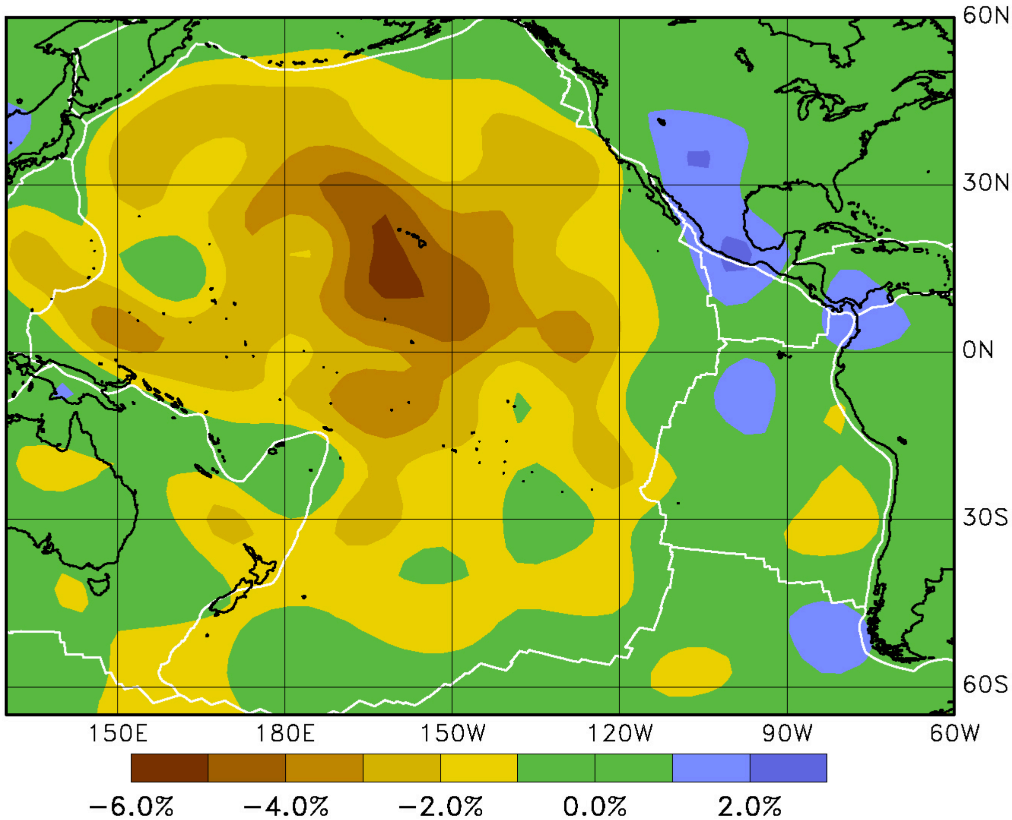

Figure 9. *Variations in polarization anisotropy (V_{SH}-V_{SV})/V_{SH} in percent) at 150 km depth under the Pacific ocean, in the model of Ekström and Dziewonski (1998). Courtesy of Göran Ekström.*

On the other hand, current large-scale seismic models cannot resolve the deep structure of the numerous hotspots present across the oceans, fueling a vigorous debate on the origin of hotspots - are they shallow features, or do they originate in the lower or lowermost mantle? While the Iceland hotspot has been the most intensely studied using local land-based network data, there is still no agreement as to whether the low-velocity, high-attenuation conduit leading to the surface expression of the hotspot extends down through the upper mantle and possibly deeper. This is due to the limited aperture of the array, confined to Iceland only. Regional tomography of the Atlantic also indicates a correlation of low velocities with hotspot locations, but resolution is still poor, as the only data available are for long paths that span from continent to continent across the Atlantic. The SWELL experiment, a short-duration deployment of a small number of long-period pressure sensors detected low seismic velocities in the upper mantle associated with the Hawaiian Swell, but the aperture of that experiment was too small to determine the lateral and depth extent of the anomaly.

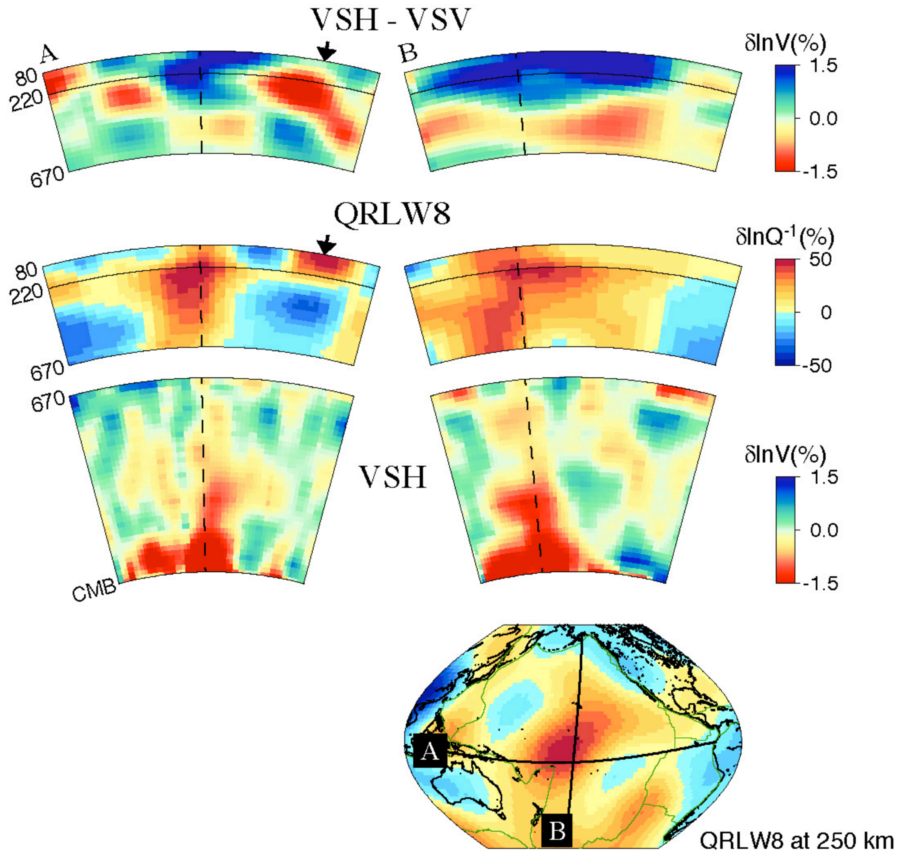

Figure 10. *Bottom panel: Map views of attenuation model QRLW8 (Romanowicz and Gung, 2002) centered on the high attenuation peaks in the Pacific. Top panels: Depth cross-sections along profiles indicated in the bottom panels showing, for each profile (top to bottom), distribution of transverse anisotropy (V_{SH}-Vsv)/V_{SH}, attenuation in the upper-mantle, and V_{SH} in the lower mantle. The upper mantle distributions are truncated at spherical harmonic degree 8, the lower mantle distributions are up to degree 24. The location of the East Pacific Rise is indicated by the arrows. Note the position of the high attenuation regions in the transition zone above the lowermost mantle low velocity minima. Zones of positive (V_{SH}-Vsv)/V_{SH} in the uppermost mantle (blue) correspond to zones where the high attenuation regions are shifted horizontally with respect to their transition zone location. Adapted from Romanowicz and Gung (2002).*

More generally, the nature of the south Pacific "superswell", its concentration of hotspots, and its relation to mantle dynamics is yet poorly understood. Global seismic models indicate a correlation between hot spot locations and the velocity distribution at the base of the mantle at the longest wavelengths (degree 2 in particular), and it has been shown that such a correlation also exists with the attenuation structure in the transition zone. More specifically, the low velocity structure at the base of the mantle beneath the south Pacific and African "superplume" regions (south Pacific and Africa) appears to extend vertically into the upper mantle, as seen from attenuation tomography. High attenuation, indicative of a high-temperature anomaly, can be traced in the uppermost mantle under the central Pacific, extending roughly over the region of strong transverse isotropy (Figure 10), and indicative of significant lateral flow in the asthenosphere. However, the resolution available from the global network data is again very poor, limited for attenuation to degrees 8 and lower (about 2500km). Progress on all these questions requires finer resolution, as can be obtained through the installation of seismic stations with the geometry proposed for the leapfrogging arrays.

Structure and dynamics of the mantle transition zone

The layered structure of the oceanic mantle has long been known to be different from that of the continental mantle. The 220 km Lehmann discontinuity does not appear to occur under the ocean basins, whereas the Gutenberg discontinuity, at shallower depth, marks a transition to lower seismic velocities under oceans. Refining these results and understanding their physical significance requires studies at regional scales, using array techniques to observe refracted and reflected waves interacting with these discontinuities, as well as deeper ones, such as the elusive 520 km discontinuity. Variations in the depth to the 400 and 660 km discontinuities have been documented on a global scale, as well as on a local scale in subduction zone regions. However, information is lacking at the intermediate scales necessary to further our understanding of the coupling between the lower and upper mantle in regions of upwellings that are preferentially located under the oceans. Finally, ocean basins are optimally located to conduct experiments aimed at confirming the possible presence of anisotropy at the base of the transition zone, critical for our understanding of the corresponding boundary layer - if it exists, and as tentatively documented in a small number of controversial studies.

Structure and dynamics of the lower mantle

The structure of the mid-lower mantle is poorly resolved in global seismic models. While downgoing slabs appear to penetrate to depths of at least 1000-1200 km under some subduction zones, their continuity at greater depths, and their relation to the ring of fast velocities around the Pacific Ocean observed in S wave tomographic models of the core-mantle boundary (sometimes referred to as the "slab graveyard") is presently tenuous and subject to questions regarding vertical resolution of the corresponding models. Seafloor observations might resolve this question. Likewise, some authors have detected seismic phases scattered from fast-velocity bodies that may represent remnant subducted slabs in the lower mantle, and, more generally, there is an indication that the lower mantle may contain widespread scatterers as seen from the analysis of precursors to core phases. Again, resolution is presently limited by the sparse distribution of seismic stations in the oceans and relatively few dense land arrays. Array studies in oceanic basins would also allow further searching for the chemically distinct, denser layer in the lower mantle proposed by some investigators. The top boundary of this layer, which should be elevated under oceans, has so far been undetected by seismology.

The most intriguing part of the deep mantle remains the last 200-300 km near the core-mantle boundary (D" region). Evidence for significant and laterally complex anisotropy has been accumulating, particularly in the Pacific Ocean, but further characterization of this anisotropy is not possible with the present distribution of seismic stations: azimuthal coverage for S-diffracted waves is required in a specific distance range, attainable only through data collection on the ocean floor (Fig. 11). Very strong and sharp transitions have been documented at the border of the African and of the Pacific superplumes, but the distribution of sources and stations results in observations being available only over very limited portions of the plumes.

Array data from the south Atlantic, south Indian and central Pacific oceans would help understand the real scale of these features and their significance in the chemistry and dynamics of the lowermost mantle. Likewise, patches of ultra low velocity zones (ULVZ's) have been documented in various areas of the world, particularly in the west central Pacific, and it has been suggested that they could mark the roots of hotspots. Yet, this evidence is circumstantial and these ideas need to be further tested by the deployment of seafloor stations that sample parts of the lower mantle inaccessible to land-based stations.

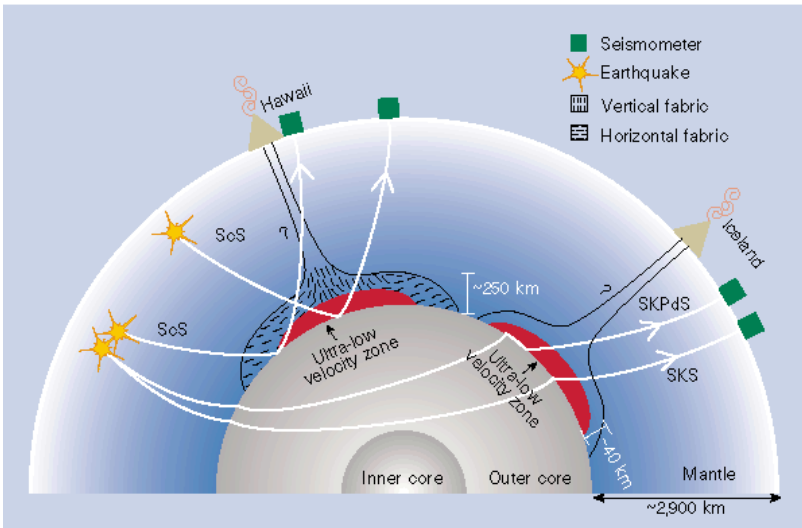

***Figure 11**. The most intriguing part of the deep mantle remains the last 200-300 km near the core-mantle boundary (D" region). Evidence for significant and laterally complex anisotropy has been accumulating, particularly in the Pacific Ocean. Seafloor seismic stations are needed to improve imaging of deep mantle structure.*

Structure of the Core

Inner core anisotropy was proposed 15 years ago to explain faster propagation of PKP phases on polar paths compared to equatorial paths, as well as anomalous splitting of core sensitive normal modes. Simple models of constant transverse isotropy can explain the data to first order. However, as high quality broadband data have accumulated, a high level of complexity has emerged, with hemispherical variations in the trends of PKP travel times, as well as evidence for layering of anisotropy within the inner core. Very anomalous paths along the South Sandwich Island to Alaska corridor cannot be explained by any simple model of the inner core and the inner core origin of these anomalies has been questioned. Some authors have argued that the uneven distribution of observations on polar paths combined with strong heterogeneity at the base of the mantle could contaminate our view of inner core structure. The possibility of lateral heterogeneity in the outer core has also been invoked, perhaps distributed as "sediments" in the immediate vicinity of the core-mantle boundary. To further distinguish the relative contributions of core-mantle boundary structure, outer-core heterogeneity and inner-core anisotropy requires a much more uniform sampling of polar paths around the globe, which implies installing arrays of stations in and around Antarctica on the one hand, in the Arctic ocean on the other.

5.3 Ocean-Continent Structure/Offshore Complement to USArray

EarthScope is a decade-long program to understand the formation, structure and evolution of the North American continent. The USArray facility will have two primary components, designed to map the structure of the entire continent and underlying mantle with high resolution: Bigfoot is a transportable array of 400 broadband seismometers that will be spaced at about 70 km intervals and systematically moved to provide nearly uniform coverage of the entire continental United States that is above sea level. The second component of USArray is a flexible array component designed to carry out higher resolution studies of more limited areas, such as individual faults, by locally increasing the density of stations. USArray and the other EarthScope components address a host of scientific questions, such as: How does strain accumulate and release at plate boundaries?, What is the nature of the Alaska and Cascadia plate boundary megathrusts and how do they affect the subduction zone seismic cycle? How is the San Andreas transform motion expressed in the mantle? What causes coast ranges and basins in forearcs? How does the continent grow? What is a continent? How are continental structure and deformation related? These and many more scientific targets are described in detail in workshop reports available through http://www.earthscope.org.

It is clear that most of these scientific questions do not stop at the shoreline; what makes a continent a continent, for example, may best be understood by studying the transition from continent to seafloor. Rather than repeating the scientific justification for USArray, this workshop concentrated on just a few of the questions that are best addressed by an offshore component and on the best way to extend USArray offshore. The primary conclusion was that the best approach would be to simply continue the USArray strategy offshore with a two-component facility: a transportable array of broadband, ocean-bottom seismometers that would be spaced at about 70 km intervals and systematically moved to provide nearly uniform coverage of the continental shelves and the transition to oceanic structure; and a flexible array that could be deployed for higher resolution studies of limited areas by locally increasing the density of stations.

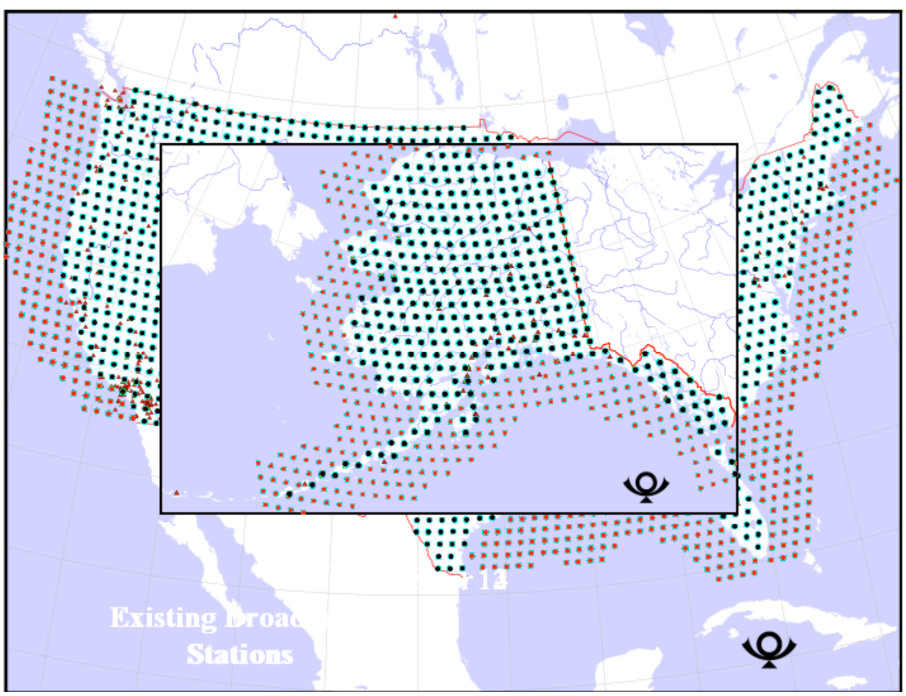

Figure 12. *USArray Bigfoot stations (in green) and proposed 'Webfoot' offshore OBS array (in red) that move with USArray around the margins of North America. Webfoot would consist of 150 OBS spaced ~70 km and will extend ~ 630 km offshore.*

The number of OBSs required is dictated by the need to extend the array about 630 km offshore to ensure that the ocean-to-continent transition is captured and to provide crossing rays for tomographic imaging of the mantle to depths of the transition zone. With 150 instruments, the needed coastal coverage of the United States including Alaska could be accomplished with 8 deployments of duration 15 to 18 months each. Because many of the seismological techniques, such as shear-wave splitting, S-wave tomography, and receiver-function analysis, require horizontal components of ground motion and horizontal noise is induced by interaction of OBSs with tidal and other bottom currents that may be stronger than on the deep-sea floor, shallow burial of the sensors is essential.

Continental-oceanic transitions

There are several types of transitions between continental lithosphere and oceanic lithosphere that may behave in different ways. Passive, rifted margins like the East Coast underwent a period of continental extension before seafloor spreading was fully established. Are there any differences in the mantle lithosphere beneath unextended continental crust, transitional extended crust, and oceanic crust formed at a spreading center? Beneath a spreading center, we expect a residual layer to be created that is depleted of volatiles and other incompatible elements, but continental lithosphere is assembled through a more complex history of differentiation, collisional accretion, underplating, and perhaps metasomatic alteration. Over what width and depth range does this transition occur? How does an old, rifted margin that has been inactive for > 150 Ma compare to an active rifted margin like the Gulf of California? Does mantle flow in the asthenosphere change when it meets the continental tectosphere? Does the oceanic asthenosphere survive under the tectosphere? Where a continental margin has passed over a hotspot, like along the Kelvin Seamount chain/Boston-Ottawa seismic zone, are both the continental and oceanic asthenospheres and/or lithospheres replaced or altered by similar upwelling from the deeper mantle? Is there any evidence of small-scale convection in the asthenosphere associated with a thermal transition from continental to oceanic lithosphere?

How does the nature of the continental-oceanic transition zone change when it is relatively abrupt and controlled by a strike-slip boundary, such as along much of the southern California coast? Does past subduction of a spreading center blur the boundary between continental and oceanic mantle, or is there still a recognizable difference? Is the deep structure beneath the extended California borderlands region similar to the deep structure beneath a stretched, rifted margin?

Plate boundary interactions

Much of the process of continent building and deformation takes place at or near plate boundaries. Key questions revolve around the role of the mantle in driving deformation, controlling geometry, or simply responding to plate motions. Along the U.S. west coast and in Alaska, there are examples of a variety of plate boundaries, ranging from the megathrusts beneath Alaska and Cascadia that generate some of the world's largest earthquakes to the complex Mendocino triple junction and the San Andreas fault that runs through some of our most populated areas. Understanding the deep structure beneath these areas requires offshore instrumentation.

A central focus of EarthScope will be the San Andreas transform boundary. What is the mantle flow field beneath the San Andreas and how does it relate to surface deformation? Does a narrow transform boundary extend into the mantle or is there a wide-zone of distributed deformation? How does the lithosphere-asthenosphere system change outboard of the fault?

There is clear magnetic and geological evidence of rotation of small crustal blocks near the San Andreas; how much of the lower crust and upper mantle rotate with the surficial blocks? How far offshore does the strike-slip deformation extend and is there a difference in fault structure between on shore faults and those offshore in thinner crust? At one time, there was a subduction zone all along the California coast; is there any evidence of obducted Farallon slab fragments in the offshore lithosphere?The San Andreas terminates at the triple junction between the Juan de Fuca, North America and Pacific plates. The southern part of the Juan de Fuca plate is seismically active and appears to be undergoing substantial intraplate deformation. What is the pattern of mantle flow where three plates interact? What are the contrasts in lithospheric properties between the deforming Juan de Fuca plate and the older, stronger Pacific plate? How does the deformation of the plate affect subduction beneath North America? What controls the abrupt change in seismicity near the junction, where thrust earthquakes in the southern Cascadia subduction zone are fairly uniformly distributed laterally in the crust but give way to highly localized San Andreas transform seismicity over a distance of 50km? As the Juan de Fuca plate subducts beneath Cascadia, how does the mantle flow change as the age of the seafloor changes from south to north? Are there structural controls over intraplate seismicity in the down-going plate? What variations are there in the depth to the top of the subducting plate and does its internal structure change as predicted by simple thermal models?

In Alaska, the boundary between North America and the Pacific plate changes from strike-slip to a subduction zone. Some parts of this boundary generate great earthquakes; other parts appear to be seismic gaps. Are there any structural or geometric differences that might indicate that the gaps might be permanent or long-term features, or are they the result of geometric irregularities on the descending plate? What changes in structure of the overriding and subducting plates are associated with the gradual transition from a broad accretionary wedge in eastern Alaska to a narrow, non-accreting boundary in the Aleutian trench? How does mantle flow in the wedge above the subducting slab change with change in dip and strike of subduction? Does the subducting slab displace the phase transitions in the mantle transition zone and does interaction with the transition zone alter the character of the subducting slab? As for southern California, is there coupling between rotating crustal blocks and the mantle flow field?

6. Relation to Other Geoscience Programs

A program in Ocean Mantle Dynamics would complement and support other major ocean and earth science programs, including RIDGE2000, MARGINS, CSEDI and EarthScope, providing many opportunities for potential collaboration among these programs.

The RIDGE 2000 Integrated Studies program is addressing the complex, inter-linked array of processes that transfer heat and material from the Earth's mantle to the crust and overlying ocean. Two of the seven major scientific questions identified in the RIDGE2000 Science Plan are: How are melt and fluid transport organized within the mantle and crust? and What are the relationships among mantle flow, mantle composition, crustal geology, ridge morphology and segmentation? These two goals clearly overlap with those of the Ocean Mantle Dynamics program. The primary emphasis of RIDGE2000 is on shallow level processes, particularly magmatic-hydrothermal-biological interactions in the ocean crust, at the sea floor, and in the overlying water column. The OMD emphasis on deeper level, mantle dynamics is thus very complementary to the goals of RIDGE2000. The opportunity exists for MELT-type 2-D or 3-D passive, teleseismic experiments at both the EPR 9°N and Lau Basin RIDGE2000 Integrated Study Sites that could be jointly supported by RIDGE2000 and OMD.

The MARGINS program seeks to understand the complex interplay of processes that govern continental margin evolution. Mantle dynamics is intimately tied to many of the key scientific questions MARGINS is addressing including magma genesis and crustal recycling, strain partitioning during deformation, and fluid fluxes. OMD supported experiments will result in a much better understanding of large scale mantle circulation for oceanic regions bordering the MARGINS focus sites and other continental margins, and new insight into how this flow interacts with the tectonics of a particular region. As in the case of RIDGE2000 there is the potential for joint process-oriented experiments in one or more of the MARGINS focus areas. A large, passive teleseismic experiment, like that envisioned for OMD, has already been funded for the Marianas MARGINS focus area for 2002-2004. The Gulf of California/Salton Trough region is a focus site for the Rupturing Continental Lithosphere initiative and another potential site for a joint OMD-MARGINS experiment.

There are also strong potential ties between OMD and major earth sciences programs such as CSEDI and EarthScope. The leapfrogging arrays envisioned by OMD will, over the course of a decade, fill in the large gaps that exist in the coverage of the Global Seismic Network and thus significantly improve images of deep and whole earth structure. This will directly contribute to the goals of the CSEDI program. As noted in section 5.3, many of the objectives of EarthScope require offshore seismic observations in order to achieve success. For example, studies of the variability and lateral changes in the architecture of continental lithosphere and asthenosphere require seafloor instrumentation on the continental margin since the edge of the continental lithosphere often occurs several hundred kilometers offshore. Recent dynamical models suggest that small-scale mantle convection often develops near the edge of old continental lithosphere, also requiring offshore sensors. The understanding of fault systems along the west coast of the US requires offshore sensors, since parts of the San Andreas fault system actually lie offshore in the California borderlands region as well as in the Mendocino Triple Junction region. Without offshore sensors, earthquakes along these faults are poorly recorded, since all the stations lie to the east of the faults. Several of the offshore faults are thought to represent significant seismic hazards to the Los Angeles basin and San Diego region, yet they are very poorly studied. Finally, an offshore deployment will provide important constraints on earthquake locations and fault structures offshore that are required for proper interpretation of the geodetic results expected from the Plate Boundary Observatory (PBO) program. Similar issues will arise in other regions of the country as USArray rolls across the country. Along the Gulf Coast and Eastern seaboard, the major scientific questions concern the properties along the edge of the North American craton. These questions include how rapidly the continental lithosphere thins towards the ocean, what pattern of mantle flow or convection is associated with the edge of the craton, and how these factors are related to the geological history, including uplift and subsidence, of the region. These questions cannot be addressed without offshore instrumentation and is an area where the objectives of EarthScope, the MARGINS program and OMD all overlap.

7. Fostering Interaction/Community Building

The OMD program will engage scientists with a broad range of backgrounds, drawing from both the earth and ocean sciences communities. This was reflected in the participants at the Snowbird workshop. Over 40% of the workshop attendees were non-seismologists including geologists, petrologists, geochemists, experimentalists and modelers. About half of the workshop participants are largely funded through the Earth Sciences Division at NSF, the remainder through the Ocean Sciences Division. This mixing of a variety of disciplines from both the earth and ocean sciences communities is relatively uncommon, and would be one of the unique aspects of an ocean mantle dynamics program.

An important function of a coordinated OMD program will be to nurture and build this community through annual workshops, short courses and other activities such as an OMD electronic newsletter. The OMD Science Plan includes plans for an annual community workshop, typically involving 50-75 participants, including faculty, post-docs and graduate students. Each workshop will focus on different aspects of ocean mantle dynamics, but will also include progress reports on results from recent experiments. The RIDGE and MARGINS Theoretical Institutes have been highly successful, and short courses like this should be sponsored from time to time by OMD. These short courses provide a mechanism to advance understanding of key theoretical problems in mantle dynamics research by fostering stronger links between field scientists, experimentalists and theoreticians, and give researchers and their students the required background to address complex, interdisciplinary problems. Finally, the OMD Program Office should develop and circulate a semi-annual electronic newsletter to keep the OMD community abreast of program activities, research results and opportunities. Through activities such as this, OMD will play a key role in building an interdisciplinary community of scientists interested in mantle convection, and help bridge the gap which often exists between the earth and ocean science communities.

8. Instrumentation Needs

The primary experimental tool of the OMD program is the ocean bottom seismograph (OBS). The three experimental components of the OMD program will operate simultaneously, and hence each must have its own independent pool of OBS. The number and type of OBS required are dictated by the specific seismological objectives of each OMD component, and specific recommendations are discussed in detail below.

As for any seismological study, the number of OBS necessary for a particular experiment is a function of array aperture and station spacing, which are dictated by the lateral and depth dimensions of the structures of interest, and the required spatial resolution. All experiments will benefit from the high signal levels generated by large earthquakes, and hence, given the occurrence-rate of these events, deployment durations of at least 1 year will be necessary for most experiments. (Where wind speeds have a strong seasonal variation, some experiments may benefit greatly from deployments that extend over two summer seasons.) Experiment durations will be a compromise between the need to record a sufficient number of high-quality events at a particular location and the need to carry out as many experiments as possible over the anticipated 10-year life of the OMD program.

Current OBS instrumentation available through the NSF-funded Ocean Bottom Seismograph Instrumentation Pool (OBSIP see www.obsip.org), can partially meet the needs of the OMD program. Indeed, the OBSIP instruments share many of the technical characteristics of portable land seismographs. These OBS all carry 24-bit digitizers with dynamic ranges of ~130 dB or better. Disk capacities are 10s of Gigabytes, sufficient to record 4 channels of 40 Hz data for well over a year. Unlike land seismographs, OBS cannot use an external time source such as GPS. The OBSIP OBS all carry low-power clocks that have drift-rates before correction of 1 ms/day or less, an accuracy that is adequate for OMD experiments. The OBSIP OBS carry high dynamic range, 3-component, seismometers that have a velocity response that is flat within the band 40 s to 10 Hz or wider, and have a self-noise that approaches or is below the USGS low-noise model in the same band. As discussed below, because the OBSIP OBSs are designed to be deployed on, rather than beneath, the seafloor, and hence are subject to tilt-generated noise, the use of a seismometer with a better long-period response (say to 120 s) would result in improved vertical-component data only. In addition to a seismometer, the OBSIP OBS carry a long-period pressure sensor that is sensitive to pressure variations in the frequency range from a few millihertz to a few Hz.

Compared with land deployments, the ocean floor can be a difficult environment in which to do seismology. Ocean-floor noise levels in the microseism band (~0.1-5 Hz) can, at some locations such as much of the Pacific ocean, be higher than at very noisy land sites, and in these areas short-period P-wave tomography studies will require long deployment durations. The low-frequency edge of the microseism peak limits the high-frequency content of S-wave arrivals available for shear-wave splitting and receiver function analyses. Shear-wave reverberations in soft sediment overlying basement, and water-column reverberations can also act to obscure short-period signals of interest.

OBSs are typically deployed by allowing them to free-fall from the sea-surface to the ocean floor, and hence the quality of the seismometer installation is subject to chance. Because the seismometer sits on rather than beneath the seafloor, tilting of the seismometer by even modest seafloor currents (~1 cm/s) results in the long-period ($T > 20$ s), horizontal-component data being of limited usefulness for teleseismic studies. However, good quality data from regional events can sometimes be recorded on horizontal components as shown by the MELT experiment. Vertical-component seismometers are less subject to tilt-induced accelerations, and because ocean-floor noise levels are low at frequencies of 0.01-0.1 Hz, OBS can record clear Rayleigh waves and long-period body waves up to periods of about 70 s. Long-period pressure sensors, unaffected by tilting, also record Rayleigh waves well to similar periods.

Burial of the seismometer in the seabed to a depth where the top of the seismometer is flush with the seafloor greatly reduces tilt-generated noise, and clear Rayleigh and Love waves can be recorded to periods of 100 s. Burial of the seismometer improves not only the surface-wave data but also the quality of receiver function determinations and measurements of shear-wave splitting parameters. The quality of long-period data from a buried seismometer is limited primarily by the seismometer response. Unfortunately, shallow burial of the seismometer does not reduce microseismic noise. A prototype broadband OBS using a second-generation, gravity-driven burial system is currently under development at WHOI.

OMD instrument needs for each major program element are described below:

Process-Oriented Studies of Mantle Circulation Many of the experiments required to address the scientific questions of interest will require upward of 50 OBS, possibly more. The MELT experiment, a good model for the experiments of interest to this group, made use of a total of 51 stations for 6 months. The number and nature of the scientific objectives identified by this group demands the capability to carry out 1 or 2 large experiments per year, or one large experiment and 1 or 2 smaller-scale experiments of a reconnaissance type. This would require a total of about 100 OBS. The NSF-funded OBS Pool will have an inventory of 110 long-deployment OBS the end of 2003. Hence with some modest augmentation, the OBSIP fleet will be adequate to carry out this component of the OMD program (recognizing that some of the OBSIP instruments will be needed for other studies unrelated to OMD). Ship time requirements will vary depending on the location of the site and the size of the array, but deployments and recoveries can usually be accommodated within a standard 3-4 week leg.

The large number of OBS deployments involved in these experiments means that it will not be feasible to bury the seismometers. This will greatly hinder certain types of studies, in particular those that would benefit from the determination of transverse anisotropy. However, the success of the MELT experiment shows that conventionally-deployed OBS can record teleseismic data with sufficient fidelity to meet the scientific objectives of this program. The MELT data have been used to determine both the shear-velocity and azimuthal anisotropy structure of the upper mantle from Rayleigh-wave dispersion, measure shear-wave splitting parameters, determine depths to the 410 and 670 km upper-mantle discontinuities via receiver functions and constrain the P-, S-, and anisotropy structure of the upper mantle from P- and S-wave travel times. Short-period (< 30 s) Love waves from regional events have also been used to determine both 1-D and 2-D SH velocity structure of the uppermost 100 km of the mantle beneath the MELT site.

Leapfrogging Array Experiments We envision operating simultaneously two arrays of 25 stations apiece that would each be deployed over an area of about 1000 x 1000 km. Each array will consist of three-component, buried, broadband seismometers capable of recording high quality data up to at least 100 sec period, as well as auxiliary instruments (long-period pressure sensors, current-meters) that will help remove correlated background noise from the seismic signals. The arrays will be deployed in each 1000 x 1000 km box for a period of one year. This deployment time is a compromise between the need to record a sufficient number of high-quality events at a particular location and the need to provide as much coverage of the ocean floor as possible over the anticipated 10-year life of the OMD program. The number of stations per array and the array aperture are dictated by the maximum cruise duration of current large oceanographic research vessels (~ 50 days). Assuming 12 hours on station to bury a broadband seismograph in the seafloor, a ship speed of 10 knots, then the total on-site time and inter-station steam time to deploy 25 seismographs spaced uniformly over a 1000 x 1000 km grid would be ~26 days. Assuming 4 hours to recover the buried seismograph, the equivalent number to pick up 25 stations would be ~18 days, making it feasible to recover and redeploy an array in a single leg if the areas are adjacent and the transits moderate in length.

Offshore Complement to USArray An offshore OBS array ("Webfoot') that would move in tandem with USArray around the coasts of North America, extend ~630 km offshore, and have a similar station spacing to USArray would require ~150 instruments. The technical specifications for these instruments include a broadband (125s - 16Hz), buried 3-component seismometer, sample rates of 1 or 40 sps, clock performance comparable to the Seascan clock, and sensor orientation to $\pm 5°$. The workshop also recommended a flexible array that could be used for complementary, process-oriented experiments in conjunction with the USArray onshore flexible array. This flexible array would have ~50 instruments equipped with a buried broadband (125s to 40Hz) geophone which could be sampled at 1, 40 or 100 sps, a short period (1-100Hz) geophone that could be sampled at 1-100 Hz, and a hydrophone.

Because ocean currents are generally much stronger on the continental shelf and along the continental margin, all of the seismometers must be buried. A sensor burial system that is effective with a 'hard' bottom (e.g. coarse, sandy sediments) will be needed. An ROV-based deployment scheme is one option, but may not be practical (or affordable) for the deployment of large numbers of OBS. Assuming 12 hours on station to bury a broadband seismograph in the seafloor, a ship speed of 10 knots, then the total on-site time and inter-station steam time for deploying 150 instruments would be ~100 days. Assuming 6 hours to recover the buried seismograph, the equivalent ship time to pick up 150 stations would be ~60 days. This number does not include transit time from port to the experiment area. ,

The total OMD instrument needs are thus ~350 OBS for all three program components (Table 1). If it is assumed that about half of the existing pool instruments will be needed for MARGINS, RIDGE2000 or core-funded projects unrelated to OMD, then a significant expansion of the pool of wideband OBS will be required for OMD. A particularly high priority is the acquisition of broadband OBS with buriable sensors. The workshop agreed that all new OBS acquired for OMD should be maintained and operated by OBSIP.

Table 1: Projected OMD Instrument Needs

	Total Need	Available	New Instruments	Cost+
(1) Process-oriented experiments (2 concurrent experiments)	100	50#	50	$2M
(2) Leapfrogging Arrays (2 arrays)	50*	-	50*	$3
(3) Offshore complement to USArray				
Flexible array	50*	-	50*	$3M
Webfoot	150*	-	150*	$9M
Total	350	50	300	$17M

* buried broadband sensor
# assumes 60 of existing OBSIP long-deployment OBS required for core-funded studies
+ assumes $40K/instr. for wideband OBS; $60K for broadband OBS with buried sensor

Table 1 also provides an estimate of the instrument acquisition costs for various program components. Supplementing the existing pool of wideband OBS for regional, process-oriented experiments (50 instruments) and constructing two leapfrogging arrays (25-instruments each) for global earth structure will require an investment of ~$5M. Developing a dedicated flexible array for process-oriented experiments to complement USArray (50 instruments) will require an additional $3M. A dedicated offshore array (or Webfoot) to move in tandem with USArray will require an investment of $9M.

There may be additional non-seismic instrument needs for some OMD experiments, specifically more electromagnetic instruments. However these needs were not well-defined at the workshop.

9. Education and Outreach

The primary mission of OMD's Education and Outreach (E&O) component will be to ensure that the OMD experiment will generate a more knowledgeable general public with greater understanding of the scientific and societal contributions made by the OMD experiment and the solid earth sciences generally. The scientific mission of OMD is defined by a set of fundamental problems concerning the nature and workings of more than 70% of our dynamic planet. These problems are ideally suited to stimulate public interest in the solid earth sciences and to attract students to the study of science and its pursuit as a career.

OMD's E&O component will achieve this mission by developing and supporting products, facilities, and programs in collaboration with a number of natural allies who share congruent science, education, and outreach goals (e.g., IRIS, EarthScope, Centers for Ocean Sciences Education Excellence (COSEE)). OMD will attempt to complement and amplify the activities of these established enterprises and also access the substantial expertise possessed by these organizations. IRIS, in particular, naturally acts as an interface to the primary and secondary education communities. Its growing commitment to public education also provides an invaluable framework in which to place OMD E&O contributions. OMD plans to have an E&O program office to coordinate these collaborations, act as a conduit for research results to educators and the general public, and mobilize OMD contributing scientists.

OMD's E&O agenda is planned to comprise three principal elements.

• OMD will promote science literacy at the K-16 level and in the general public. This element will be composed of at least three parts. First, OMD will contribute to IRIS E&O workshops aimed at secondary and non-research college educators, which take place, for example, at the National Science Teachers Association (NSTA) meetings and elsewhere. IRIS would value well coordinated contributions from collaborating science initiatives. Second, OMD will host a teacher-at-sea (TOS) program which will be coordinated with existing programs and with input from COSEE. Identification of participants will be facilitated through the IRIS E&O workshops. Finally, OMD plans to develop a variety of educational resources including the creation of posters, fact sheets, news releases, educational videos, supplemental curriculum resources, and museum exhibits. Again, OMD will use IRIS's success in these areas as a guide.

• OMD will train and develop a new cadre of interdisciplinary earth scientists by advancing formal earth science education and providing research opportunities for students. First, OMD will host a number of undergraduate summer student interns. The plan, at present, is to coordinate this venture through IRIS's internship program. Second, OMD envisions a competition to foster undergraduate research projects performed at non-research colleges and universities. Finally, concerning graduate education, OMD is defined by cutting edge research projects involving broad-based interdisciplinary training in the earth sciences which provides a model for cross-cutting scientific education.

• OMD's E&O component will be the public face for the experiment and work with its allies to promote solid earth science. In this role, the E&O component will act to create a high-profile identity for OMD that emphasizes the scientific problems that OMD is addressing, the multidisciplinary nature of the avenues taken to solve these problems, and the general interest and importance of the OMD research initiatives.

Outreach and Education initiatives remain relatively new, so careful assessment of the E&O component of OMD is needed to ensure its responsiveness to its intended audience and its effectiveness in achieving its goals. The evaluation process will evolve to meet the changing needs of the E&O program.

10. Management

There was a strong consensus at the workshop that projects supported by OMD should be coordinated and interdisciplinary, involving geophysicists, petrologists, geochemists and modelers. It is this coordinated, interdisciplinary approach, and the need to plan and schedule for community use mobile, broadband OBS arrays, that sets this program apart from normal investigator-initiated projects and argues for the establishment of an OMD program. The workshop attendees also noted that a *program* in ocean mantle dynamics could also play a critical role in bringing together a community of researchers from the earth and ocean sciences that do not normally work together, but that have overlapping research interests.

Program Management - OMD program management will be based on the RIDGE model. Projects will be selected by competitive peer review through the normal NSF Ocean Sciences panel structure. Projects eligible for funding through OMD will have to be certified as relevant to the goals of the OMD program by an OMD Steering Committee. The Steering Committee may from time to time work with NSF to issue program announcements to insure that the longer-term goals of the program are achieved. However, the OMD philosophy is to provide as much freedom as possible to individual groups of investigators to choose the locations and processes they wish to study (within the framework of the long-term OMD scientific objectives), and to let the peer-review process prioritize the projects that are funded and where these experiments are carried out.

An OMD Steering Committee will be established to oversee the implementation of the OMD Science Plan. The OMD steering committee will comprise a minimum of six members, two each from the seismology, petrology/geochemistry, and geodynamics/geophysics communities, plus a chair and, as ad hoc members, any subcommittee chairs. The OMD Steering Committee will be responsible for a relevancy review of proposals, selection of an annual workshop topic, appointment and recruitment of a workshop committee, selection of annual PIs for the leapfrogging arrays, and selecting the next chair and new members. The Steering Committee is also responsible for coordination with other major geoscience programs such as EarthScope, R2K and MARGINS and overseeing OMD E&O programs. The Chair of the steering committee and Chair's office is responsible for organizing meetings of the steering committee, providing logistical support for the workshop committee, maintaining a web site for news items and communication, producing a semiannual electronic newsletter, monitoring prompt delivery of data sets to data management center, and acting as spokesperson for the initiative when necessary. Small subcommittees may need to be established by the steering committee to oversee the initial stages of the leapfrogging and Webfoot components of the OMD program. The Chair of the Steering Committee will be appointed for a three-year term. The steering committee members will be appointed for 2 or 3 year terms, with rotation beginning after the second year.

Facility Management - OMD will utilize the National Ocean Bottom Seismic Instrumentation Pool (OBSIP) to provide basic facility support for the program. OBSIP will provide the instruments and at-sea technical support for conducting OMD seismic experiments. As noted in Section 8, OMD will require construction of additional OBS, including broadband OBS with buriable sensors. It is envisioned that these additional instruments would be built by OBSIP and operated as part of the national OBS pool. We anticipate that the OMD Steering Committee and the OBSIP Management Committee would work closely to insure that these new instruments meet the future needs of the program. Because of the interdisciplinary nature of OMD experiments, other instrumentation will be required from time to time including multibeam mapping systems, EM/MT instruments, gravimeters, heat flow probes, and bottom sampling. Scheduling of these other tools will be on a project-by-project basis.

The scheduling of the leapfrogging and offshore-complement-to-EarthScope arrays will require special coordination. Practical considerations suggest that the leapfrogging array should be funded for say a 5-year period, and that the array move from location to location in such a way as to minimize transits between sites. The OMD Steering Committee will need to oversee a process that develops a 5-year deployment schedule, and identifies each year's project leaders. Webfoot will require close coordination with the USArray, as its deployment schedule would be directly tied to USArray. The scheduling of the 'flexible' offshore array described in Section 5c would be experiment-driven and determined through the normal peer-review process. In some cases (e.g. off southern Calif.) it might not have to be tied to the USArray deployment schedule.

Data Management - Seismological data sets collected by OMD projects will be archived at the IRIS Data Management Center within six months after the recovery of the instruments. The individual OBSIP Institutional Instrument Centers will be responsible for data quality control and for preparing metadata for submission to the IRIS DMC. Data will be available for general public use immediately in the case of the community experiments (leapfrogging arrays, offshore USArray component), and within two years after instrument recovery in the case PI-initiated projects). Non-seismic data collected in OMD projects will be made available according to established NSF OCE data policies.

11. Resource Requirements/Timeline

The primary resources required are for construction and operation of ocean-bottom seismometers, support of science (PIs), ship time for deployment and recovery, and workshops/management. Total construction costs are estimated above in Table 1. Other costs are estimated below and a rough timeline for the program is outlined in Table 2. There are three main differences between this plan and that described in the Oceanic Mantle Dynamics Science Plan published in July 2000. First, it was envisioned at that time that there might be an oceanic component as an integral part of USArray, so no resources were explicitly identified for Webfoot in the initial plan. Second, seismologists at the workshop in Snowbird recognized that resolution of regional upper mantle structure and detection of systematic changes in waveforms needed for deep earth imaging would both be much enhanced if the number of OBS in each leapfrogging array were expanded from the ten suggested in the original report to 25, thus increasing both instrument costs and ship time needed for deployment. Third, with the addition of Webfoot and an expanded educational component, total management costs are increased.

Table 2a. Cost estimates for integrated, focused experiments

Year	OBS construction	Analysis & Shore-based	Deployment & Recovery	Ship days	Total (not incl ship time)
2004	$1.0M	$3M	$0.8M	80	$4.0M
2005	1.0	4.2	1.2	160	6.4
2006		4.2	1.2	160	5.4
2007		4.2	1.2	160	5.4
2008		4.2	1.2	160	5.4
2009		4.2	1.2	160	5.4
2010		4.2	1.2	160	5.4
2011		4.2	1.2	160	5.4
2012		4.2	1.2	160	5.4
2013		4.2	1.2	160	5.4
2014		3.0	0.8	80	3.8
2015		1.8			1.8
2016					

The principle time-critical factor is the need for coordination of Webfoot with the Bigfoot component of USArray. In order to deploy simultaneously with Bigfoot, development of ocean-bottom seismometers with sensors that can be buried needs to begin immediately. The first Bigfoot deployment is expected to begin in Southern California, followed by expansion of the array northward along the west Coast in years 2 and 3. Bigfoot will then move eastward into the interior of the western U.S.. As it moves eastward, in years 6 through 10 it will be in the vicinity of the coast of the Gulf of Mexico, Great Lakes, and the East coast, followed by years 11 and 12 in Alaska. There is some question about how rapidly buried OBS could be ready. It is desirable to have the Webfoot program ready to begin in year 1 of EarthScope, but because there is a relatively high density of permanent, broadband stations in southern California, Webfoot would still be effective if deployed there in years 4 and 5. It is essential, however, that Webfoot be deployed to complement the Bigfoot deployment in the Pacific Northwest in years 2 and 3 of EarthScope. Deployment duration should be 15-18 months.

We are assuming ten full years of focused field programs, with a ramp-up year and ramping down over a two-year period. Similarly, ten full years of leapfrogging array operation are planned, with a ramp-up period for construction of ocean-bottom seismometers. Webfoot will have to coincide with EarthScope, currently expected to conclude in about 2016.

Focused, interdisciplinary field programs: We assume a typical major field program will involve a 3-to-4 yr grant for ~$1.6M for science costs + $0.8M for OBS deployment costs + ship costs and that there will be an average of 1.5 such projects each year. The $1.6M figure includes all science support costs for seismic data analysis and interpretation, and associated petrology/geochemistry and other geophysical costs. Although each experiment will have different instrument requirements, in order to provide a budget projection we assume an average experiment will use 50 OBS @ $16K/instrument or ~$0.8M/experiment in instrument support costs. We also estimate each experiment will require two or three ~40 day legs to carry out OBS deployment/recoveries and ancillary sampling and surveying, for a total of 4 legs/yr on average, assuming 1 to 2 major field programs per year.

Table 2b. Cost estimates for leapfrogging arrays and management

Year	OBS construction	PIs and Management*	Deployment & Recovery	Ship days	Total (not incl ship time)
2004	$1.0M				$1.0M
2005	2.0				2.0
2006		$0.6M	$0.6M	75	1.2
2007		0.6M	1.0	100	1.6
2008		0.6M	1.0	100	1.6
2009		0.6M	1.0	100	1.6
2010		0.6M	1.0	100	1.6
2011		0.6M	1.0	100	1.6
2012		0.6M	1.0	100	1.6
2013		0.6M	1.0	100	1.6
2014		0.6M	1.0	100	1.6
2015		0.6M	1.0	100	1.6
2016			0.4	75	0.4

* Management covers management of all three components

Shore-based ancillary investigations: We anticipate ~10 projects per year, including laboratory experiments and analysis, geodynamical modeling, and analysis of existing data sets or data sets from prior experiments including leapfrogging arrays, typically a 2 year grant for ~$180 K total.

Leapfrogging arrays: a leapfrogging array proposal is assumed to be a 2-year, $150K grant for each year's PI + $500K in OBS deployment costs + ship costs. The OBS costs are estimated assuming 25 instruments with a buried wide-band sensor at $20K/instrument. Two 50-day legs will be required each year for OBS deployment/recoveries, although at the beginning or end of the experiment when only deployments or recoveries are being made, 35-40 day legs would suffice. We are assuming that data from leapfrogging experiments will be viewed as a resource for global seismological studies that in most cases will be funded through the normal process in Earth Science. Data distribution through the IRIS Data Management Center will entail no significant additional costs.

Webfoot: Two deployments of 15-18 months required to cover each of the coasts: west coast, Gulf/Florida/Great Lakes, east coast, Alaska. 75 ship days required to deploy or recover each array + $3M for OBS deployment costs @ $20K/instrument for buried instruments. Although the general configuration of the arrays is pre-determined, principal investigators will have to be supported to select the particular sites and oversee the actual deployment. Because the arrays will be an extension to USArray's Bigfoot and naturally included in analyses of continental structure, we have not included separate funds for data interpretation in this budget.

Flexible offshore field programs: One major seismological field program per year on U.S. continental margins with a focused deployment of OBSs to complement the sparser, broader Webfoot array, with costs of $0.5M for science + $0.8M for OBS deployment + ship costs. Each experiment will require two ~40 day legs for deployment and recovery of OBSs and ancillary measurements

Table 2c. Cost estimates for Webfoot and offshore flexible component

Year	OBS construction	Siting PIs + Offshore Flex	Deployment & Recovery	Ship days Web+Flex	Total (not incl ship time)
2004	$2.0M				$2.0M
2005	6.0				6.0
2006	4.0	$0.3 + 0.5M	$1.8 + 0.8M	100 + 80	7.4
2007		0.3 + 0.5	1.2 + 0.8	60 + 80	2.8
2008		0.3 + 0.5	1.8 + 0.8	100 + 80	3.4
2009		0.3 + 0.5	1.2 + 0.8	60 + 80	2.8
2010		0.3 + 0.5	1.8 + 0.8	100 + 80	3.4
2011		0.3 + 0.5	3.0 + 0.8	160 + 80	4.6
2012		0.3 + 0.5	3.0 + 0.8	160 + 80	4.6
2013		0.3 + 0.5	3.0 + 0.8	160 + 80	4.6
2014		0.3 + 0.5	3.0 + 0.8	160 + 80	4.6
2015		0.3 + 0.5	3.0 + 0.8	160 + 80	4.6
2016		0.3 + 0.5	1.2 + 0.8	60 + 80	2.8

Workshop/management/education: One workshop each year will focus on different aspects of mantle dynamics and progress reports on interpretation of experiments. Education component and periodic short courses may be executed on a grant basis, but supervised or coordinated through the management office. Total about $300K/yr.

12. Workshop Recommendations

The workshop adopted the following recommendations and conclusions:

- *A decade-long program of focused, coordinated studies, centered around experiments made possible with a new generation of ocean bottom seismic instrumentation and incorporating constraints from petrology, geochemistry and geodynamic modeling, could make tremendous progress towards solving the outstanding questions of mantle dynamics*
- *An Ocean Mantle Dynamics (OMD) program should have three major components: (1) large, process-oriented, interdisciplinary OBS experiments and related shore-based studies to test current models of mantle circulation; (2) two leapfrogging regional arrays of OBS to fill in gaps in the global seismic network and improve resolution of global earth structure;, and (3) an offshore complement to USArray to study ocean-continent crustal and upper mantle structure*
- *An OMD program should foster an interdisciplinary approach to addressing mantle dynamics problems involving seismologists, petrologists, geochemists, geophysicists, modelers, theoreticians and experimentalists from both the ocean and earth science communities*
- *An Executive Steering Committee for an OMD program should be established immediately to continue development of the OMD program and coordinate with other major geoscience initiatives (RIDGE2000, MARGINS, EarthScope)*
- *The existing pool of broadband ocean-bottom seismometers (OBS) should be expanded, including the immediate development of OBS with buried, broadband sensors*
- *OMD should encourage the development of standardized geochemical data sets that have all analyses performed on the same samples and with availability comparable to that now existing for seismic data*
- *OMD should seek new support for an offshore complement to USArray OMD represents an unusual alliance between Earth and Ocean scientists and thereforeseeks support from both the Division of Earth and the Division of Ocean Science*
- *The possibilities for international cooperation in this initiative should be fully explored*

13. Figure References

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Appendices

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TOTAL = 75

2) Workshop Agenda

Oceanic Mantle Dynamics Workshop
Snowbird, Utah
September 18-20, 2002

AGENDA

Wednesday, September 18th AM

Introduction/Goals of Workshop: *Bob Detrick (WHOI) and Don Forsyth (Brown)*

Keynote talks on outstanding questions in upper mantle dynamics/earth structure:

8:45 - 9:15	A geophysical perspective on outstanding questions in upper mantle dynamics/earth structure *Jim Gaherty (Georgia Tech)*
9:15 - 9:30	Discussion - Provocateur: *Sean Solomon (DTM)*
9:30 - 10:00	A petrological/geochemical perspective on outstanding questions in upper mantle dynamics/earth structure *Charles Langmuir (Harvard)*
10:00 - 10:15	Discussion - Provocateur: *Stan Hart (WHOI)*
10:15 - 10:45	Break/poster viewing
10:45 - 11:15	A modeler's perspective on outstanding questions in upper mantle dynamics/earth structure: *Neil Ribe (IPG, Paris)*
11:15 - 11:30	Discussion - Provocateur: *Garrett Ito (Univ. of Hawaii)*
11:30 - 12:00	Advances in Seismic Instrumentation: *Spahr Webb (L-DEO)*
12:00 - 12:15	Discussion - Provocateur: *Jim Fowler (IRIS)*
12:15 - 1:30	Lunch and poster viewing

Wednesday, September 18th PM

OMD concept and exemplary experiments

1:30 - 1:45	OMD concept: *Don Forsyth (Brown)*
1:45 - 2:15	Discussion - Provocateur: *Bob Detrick (WHOI)*

OMD-type notional experiments:

Mid-ocean ridges

2:15 - 2:30 MOR notional experiment (EPR): *Doug Toomey (Univ. of Oregon)*
2:30 - 2:45 MOR notional experiment (MAR): *Donna Blackman (Scripps/IGPP)*

Mantle plumes

2:45 - 3:00 Plume notional experiment (Hawaii): *Gabi Laske (Scripps/IGPP)*
3:00 - 3:15 Plume notional experiment (Iceland): *Yang Shen (GSO/URI)*

3:15 - 3:45 Break/poster viewing

Margins
3:45 - 4:00 Active margins notional experiment: *Doug Wiens (Washington Univ.)*
4:00 - 4:15 Rift/transform margin notional experiment: *Monica Kohler (USC)*

Mid-plate processes
4:15 - 4:30 Anisotropy notional experiment: *Paul Silver (DTM)*

Earth structure (applications of leapfrogging array)
4:30 - 4:45 Earth structure: *Mike Ritzwoller (Univ. of Colorado)*
4:45 - 5:00 Earth structure: *Michael Wysession (Washington Univ.)*

5:00 - 7:00 Reception and poster viewing

Thursday, September 19th AM
Introduction
Relationship of OMD to other major geoscience programs

8:30 - 9:00 OMD and MARGINS: *Doug Wiens (Washington Univ.)*
9:00 - 9:30 OMD and R2K: *Maya Tolstoy (L-DEO)*
9:30 – 10:00 OMD and USArray/PBO: *Paul Silver (DTM)*
10:00 - 10:30 OMD and Ocean Seismic Network: *John Orcutt (SIO/IGPP)*

10:30 - 11:00 Break/poster viewing

Developing an OMD science plan

11:00 - 12:15 Break up into working groups to discuss implementation of OMD

OMD and USArray/PBO Working Group:
co-chairs: *Alan Levander (Rice) & Frank Vernon (SIO/IGPP)*
Leapfrogging array Working Group:
co-chairs: *John Collins (WHOI) & Barbara Romanowicz (UC Berkeley)*
Ancillary studies Working Group:
co-chairs: *Dave Bercovici (Yale), Emily Klein (Duke) & Dave Kohlstedt (Univ. of Minnesota)*

12:15 - 1:30 Lunch and poster viewing

Thursday, September 19th PM
1:30 - 3:00 Working Groups reconvene
3:00 - 3:30 Break/poster viewing
3:30 - 5:30 Working Groups reconvene
6:00 - 8:00 Conference Dinner

Friday, September 20th AM

8:30 - 10:30 Final plenary session to hear reports of working groups and to discuss general program management issues and approve workshop recommendations

Moderators: *D. Forsyth and R. Detrick*

Friday, September 20th PM

1:00 – 5:00 Workshop Organizing Committee and Working Group Chairs meet to draft Workshop Report

3) Working Group Questions

Process- Oriented Experiments

- Without directing research, how can diverse experiments on Oceanic Mantle Dynamics be integrated into a coherent program?
- What are some of the critical questions that a joint geochemical/petrological/seismological experiment could address?
- In what cases should petrological studies, electromagnetic experiments, or other observations be integrated with seismological experiments studying oceanic mantle dynamics?
- Are there critical developments in geodynamic modeling, knowledge of physical properties, or understanding of melting processes that need to be addressed for prediction of observables in large-scale, interdisciplinary experiments?
- Data Management
    - Archival of seismological data - exclusive use period
    - Archival of other types of data
- How can communication between disciplines be improved?
- Should there be an annual OMD workshop?

Leap frogging arrays:

- What are the technical requirements for instruments?
    - Buried or seafloor?
    - Broadband, but how broad is broad?
    - Other specifications? Clocks? Instrument orientation?
- What instrument development work is needed?
- How many instruments in an array?
- Constraints on array spacing?
- How many arrays?
- Where should the arrays be placed and in what order?
- How long should each array be in place?
- Servicing of arrays and redeployment
    - Can they be refurbished at sea?
    - How many spares?
- Management of project
    - Separate PI for each array?
    - Overall coordination
    - Selection of responsible instrument group
- Data Management
    - Archive at IRIS DMC
    - Preparation for archival - who?
    - Data quality control
    - Any preferential access by PI

Complement to USArray:

- What are the technical requirements for instruments?
    - Buried or seafloor?
    - Broadband, but how broad is broad?
    - Other specifications? Clocks? Instrument orientation?
- What instrument development work is needed?
- Problems with fishing activities?
- Number of instruments or density of coverage needed?
- Mechanism for selecting individual sites within an array
- How to coordinate with USArray
- When will the instruments be needed?
- How many deployments with what duration?
- How far oceanward should the array extend?
- Management of project
    - Overall coordination
    - Selection of responsible instrument group
    - Outreach activities - coordination with EarthScope
- Data Management
    - Archive at IRIS DMC
    - Preparation for archival - who?
    - Data quality control