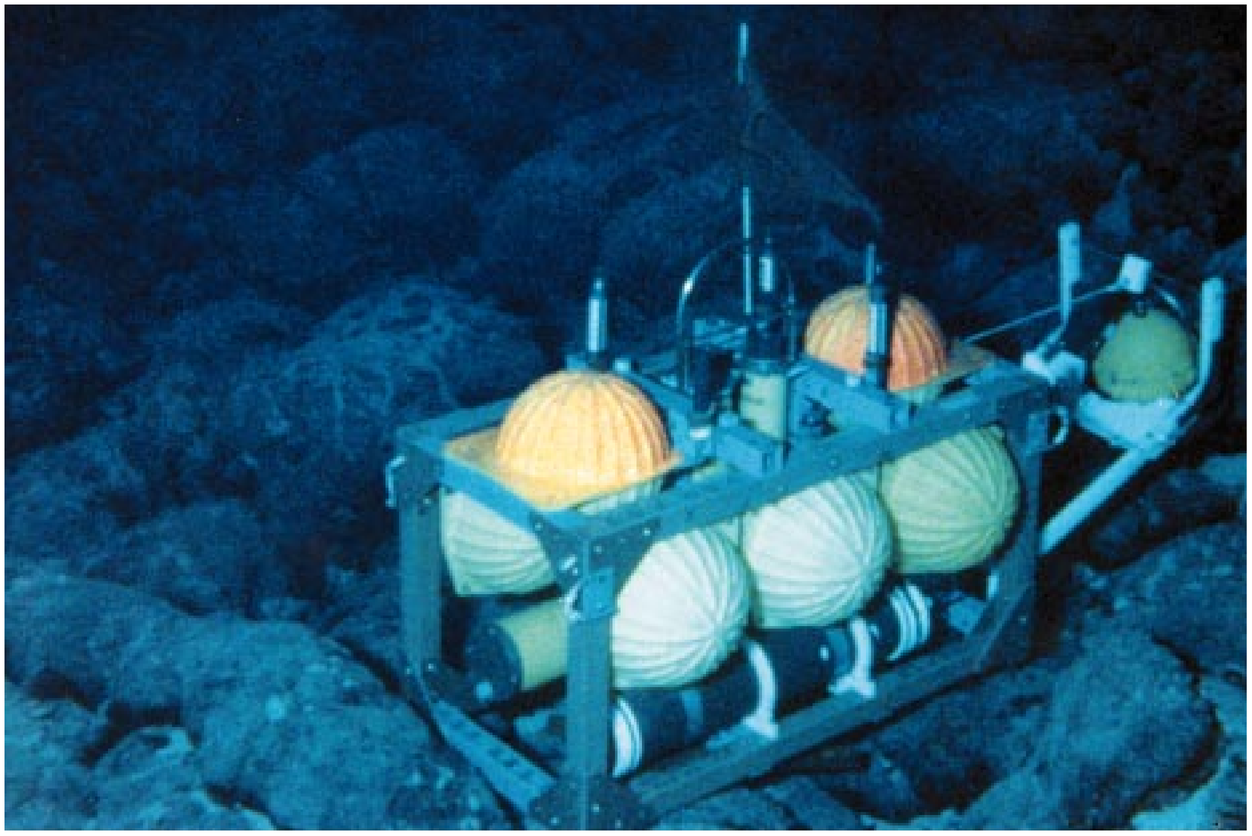
Oceanic Mantle Dynamics

SCIENCE PLAN

An Interdisciplinary Initiative to Study the
Dynamics of the Oceanic Upper Mantle



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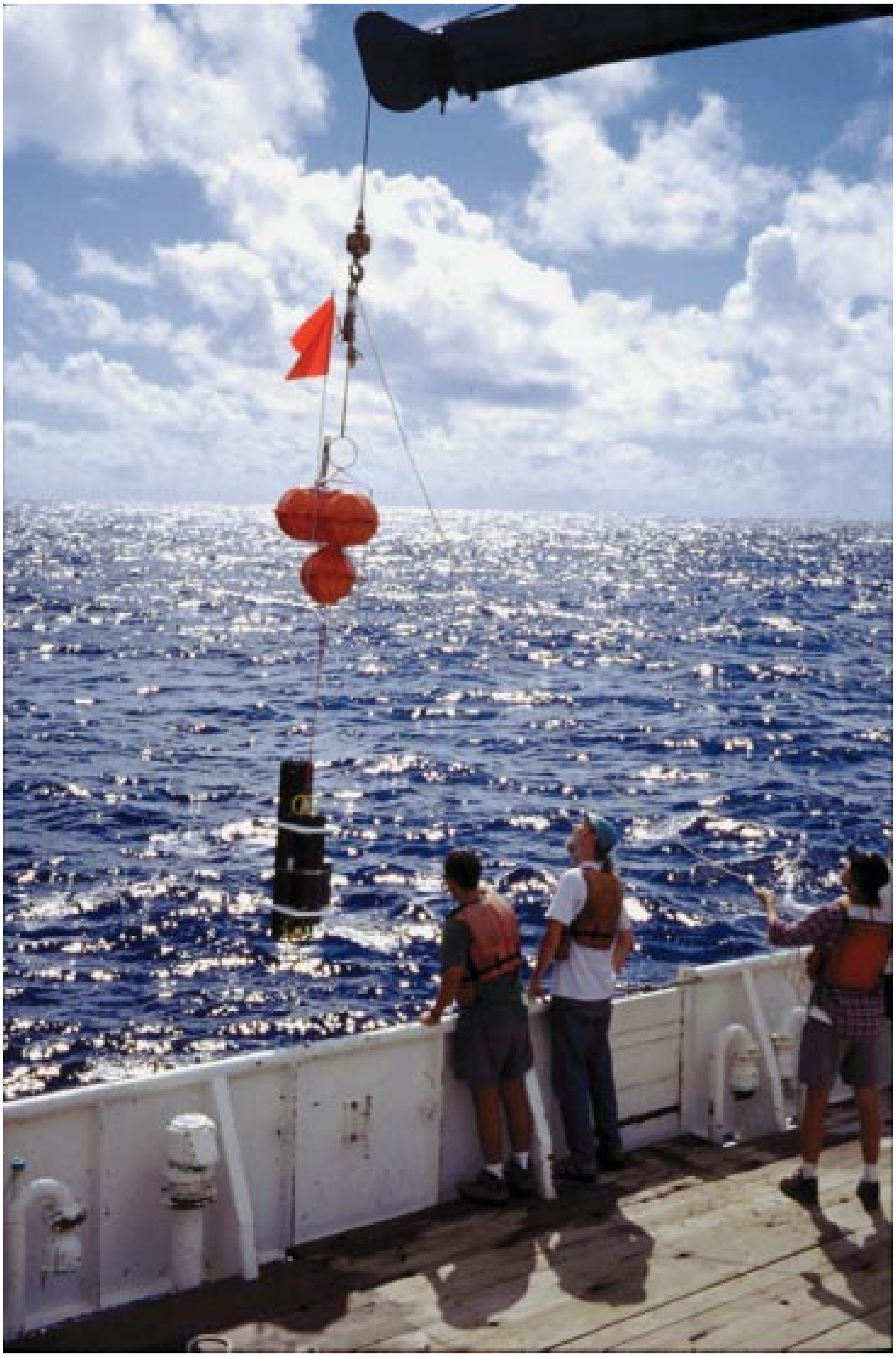

A Scripps Institution of Oceanography L-Cheapo instrument equipped with a broadband differential pressure gauge sensor being deployed for the SWELL experiment. (Photo courtesy of J. Babcock, SIO/IGPP)

Front Cover: Ocean Bottom Seismometer (OBS) from Woods Hole Oceanographic Institution sitting on young pillow basalts at the Mid-Atlantic Ridge. (Photo courtesy of F.B. Wooding, WHOI)

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Executive Summary

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 upwelling beneath island arcs, back-arc basins, mid-ocean ridges and intraplate volcanic centers.

Now, for the first time, we are entering an era when these theoretical models of mantle flow can be tested and refined with measurements in the oceans that have the power to resolve subsurface structure at the critical length scales. The establishment of a U.S. National Ocean Bottom Seismometer Instrument Pool (OBSIP) with a total of more than 100 long-duration, intermediate-band OBSs provides a tremendous opportunity for dramatic progress in understanding the dynamics of flow in the upper mantle beneath the oceans. To exploit this new resource and recent advances in seismological imaging, geochemical analysis, and geodynamic modeling, a new, decade-long, **Oceanic Mantle Dynamics (OMD) Initiative** should be established.

In a decade of focused experiments, tremendous progress could be made towards solving the outstanding geodynamical questions of the oceanic upper mantle. At least one example of all of the major types of oceanic tectonic settings recognized today could be investigated, and global seismic coverage could be obtained to improve imaging of deep earth structure. An OMD Initiative should have the following components:

1. One to two major ocean bottom seismic experiments per year utilizing OBSIP instruments would provide the central focus for the OMD Initiative

2. Major projects would also involve geochemical, petrological, geodynamic and other geophysical approaches

3. Leapfrogging regional arrays of OBSs would complement process-oriented experiments and help improve resolution of global earth structure

4. Each year during the decade of the OMD Initiative, approximately ten ancillary studies of modeling, experimentation and analysis would be carried out to deepen understanding of physical and chemical processes and to refine modeling of dynamic processes

5. All projects would be funded through competitive peer review

6. One workshop each year would provide an opportunity to discuss results of recent experiments, design new ones, and promote interaction amongst investigators from different disciplines

7. A small management office would provide a focal point for communication, workshop organization, and coordination of the leapfrogging array program

A multidisciplinary approach centered on experiments made possible by the new OBS instrumentation pool, and incorporating constraints from petrology, geochemistry and theoretical modeling of geodynamic processes, could go far toward testing and refining models of mantle flow developed in the three decades since the plate tectonic revolution.

1.0 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 upwelling beneath island arcs, back-arc basins, mid-ocean ridges and intraplate volcanic centers.

Now, for the first time, 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 on developing global tomographic models of 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 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, high resolution images have been obtained in only a few areas where stations can be placed on islands and/or 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 (OBSs) 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 with a total of more than 100 long-duration, intermediate-band OBSs available for use by the broader geophysical community (see Appendix 1), there is a tremendous opportunity for dramatic progress in understanding upper mantle processes beneath the oceans.

The purpose of the proposed initiative is to develop an organized program of research focused on problems of flow in the oceanic upper mantle. A multidisciplinary approach centered on experiments made possible by the new OBS instrumentation pool and incorporating constraints from petrology, geochemistry and theoretical modeling of geodynamic processes could go far toward testing and refining models of mantle flow developed in the three decades since the plate tectonic revolution. The intent is that this Oceanic Mantle Dynamics (OMD) Initiative will involve scientists with a broad range of backgrounds, drawing from both the earth and ocean science communities. In many ways, this initiative will be complementary to EARTHSCOPE, and the planned USArray, which will provide unprecedented imaging of the upper mantle beneath North America. In addition to providing comparable imaging of critical areas in the oceans, an OMD Initiative will help fill in gaps in global coverage and in conjunction with USArray deployments could probe the deep structure underlying ocean-continent transitions.

2.0 Outstanding 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 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:

- At what depth does melting begin beneath mid-ocean ridges?

- How is melt extracted from the mantle and focused to the ridge axis?

- Is there a spreading rate dependence to the relative importance of plate-driven vs buoyancy-driven flow?

- What is the pattern and scale of small-scale convection beneath cooling lithospheric plates?

- From what depth do mantle hotspot plumes originate?

- How large are plumes? What are the relative roles of thermal and chemical heterogeneities in plume buoyancy?

- How do plumes interact with the lithosphere to form hotspot swells?

- How do hotspots alter flow patterns near mid-ocean ridges? Are distinct channels formed connecting ridges and off-axis hotspots?

- During trench rollback, what is the pattern of flow around the sinking plate?

- What are the dimensions of the melt production region beneath back-arc basins?

- What is the ultimate fate of subducted slabs?

In the following sections, we describe the advances in ocean bottom seismic instrumentation and seismic imaging techniques, isotopic and trace element geochemistry, and theory and computational modeling that leave us poised to make unprecedented advances in our understanding of the dynamics of flow in the sub-oceanic mantle. These advances make this initiative particularly timely.

USGS/Hawaii Volcano Observatory

3.0 Advances In Capabilities

A new initiative to study the dynamics of the oceanic upper mantle is motivated by advances in seismic instrumentation and our ability to image upper mantle structure, the development of powerful new geochemical and petrological techniques, and major advances in geodynamic theory and modeling.

3.1 Advances In Seismic Imaging Of The Oceanic Upper Mantle

Flow in the upper mantle can be detected and constrained by seismological observations because elastic wave velocities and attenuation are affected by temperature, the presence of melt, the volatile content of the solid and crystalline fabric developed through dislocation creep of the solid. All of the tectonic processes described above produce predictable temperature anomalies and distinctive strain patterns. Many involve upwelling that produces various degrees of partial melting and associated volcanism.

Figure 1. *Webb OBS, one of the new generation of wide-band, long-deployment OBS that can be used in studies of the oceanic upper mantle. (photo courtesy of R. Detrick, WHOI)*

The ability of seismology to detect the effects of flow is limited by the distribution of sources and receivers, signal-to-noise ratio, and the inherent limitations of resolution from waveforms covering a limited frequency band. In the past, the primary limitation has been instrumental; OBSs could only record for 30 to 40 days, clock drift was a problem, and instrumental noise restricted useful observations to the largest earthquakes. Now, OBSs can record autonomously for a year or more and clock corrections can be made accurate to within a few ms in a year's time (Figure 1). In recent experiments, Rayleigh surface waves from moderate size events ($M_w \geq 6$) have been routinely recorded in the 15 to 60 s period band on differential pressure gauges (DPG) and vertical seismometers. Measurements extend to 70 s or more for the largest events, with the limitation being in situ pressure variations due to internal gravity water waves for the DPGs and instrumental noise for the vertical component. Improvements in sensor and amplifier design will allow measurements to 100 s routinely for moderate-sized earthquakes, so in future experiments the primary limitation will be earth noise, not instrumental.

The Ocean Seismic Network (OSN) pilot experiment demonstrated that simple burial of the sensor package greatly reduces long-period noise on the horizontal components. Even without burial, in the MELT Experiment useful measurements were obtained of shear-wave splitting, P-to-S conversions at upper mantle discontinuities, S-wave travel-time delays, P wave angle of incidence, and short-period Love waves, all requiring use of the horizontal components. These measurements would be enhanced by burial of the sensors, but each experiment will have to consider the trade-off between reduced horizontal noise and increased cost and effort of deployment.

The NSF has recently established a national OBS Instrument Pool (OBSIP) and funded the construction of over 100 long-deployment, three-component OBS suitable for broadband seismic studies in the oceans (see www.obsip.org for more details). All instruments will be equipped with state-of-the-art, low-power, 24-bit data loggers, high-precision clocks, and large-capacity disks allowing continuous data recording for a period of a year or longer. The instruments in the OBSIP will be available for use by any interested U.S. investigator. The OBSIP will provide information to potential users on the availability of Pool instruments, and will work with users to match their scientific needs with available instrumentation. The institutional instrument contributors to the national Pool (L-DEO, Scripps and WHOI) will provide complete operational and technical support for OBS operations at sea. The cost of OBS operations (e.g., shipping, instrument charges, and technical support) will be funded through the Pool. Data will be provided to users in a standard PASSCAL SEGY or SEED format. The availability of these instruments in large numbers will open up a new era in marine seismology and is one of the prime motivations for considering a focused initiative in mantle dynamics at this time.

3.2 Advances In Geochemical And Petrological Approaches

Oceanic volcanism, whether at spreading centers, hotspots or back-arc basins, results from melting of the mantle. The erupted melt thus records information on the physical and chemical conditions by which melt is produced in the mantle and the processes of melt migration and differentiation that occur en route to the surface. Advances in geochemical and petrologic studies over the past decade, including newly emerging analytical and sampling techniques, provide essential constraints on conditions in the mantle wherever melt is produced. Performed in concert with geophysical investigations, geochemical studies offer a powerful complementary perspective, and together the two approaches promise an unprecedented, integrated understanding of upper mantle dynamics in space and time.

Apart from shallow level crystallization, the dominant factors believed to affect the compositions of melts are the conditions of melting (temperature, pressure, style of melting), the reaction of melt with the mantle as it ascends to the surface (reactive porous flow vs. channelized flow), and the source composition (distribution of lithologic and/or chemical heterogeneities, etc.). Distinguishing the signal produced by each process requires the full arsenal of geochemical analyses and experimental approaches. Many of the essential types of analyses are well-established, such as major element, trace element and radiogenic isotopic analyses of basalt glasses (e.g., electron microprobe, OES, ICP-MS and TIMS). Such studies, combined with experimental constraints, have been used successfully to identify variations in extents of melting, pressures of melting, and the style of melting (e.g. fractional, dynamic, batch, etc.). Other techniques, however, are just coming into use and the power of these new analyses, combined with the information from more standard analyses have yet to be fully exploited.

Figure 2. *Melt inclusions (brown) up to 200 microns in diameter in a high-Mg olivine host from an oceanic basalt. Analysis of these melt inclusions are providing new information on the isotopic and incompatible trace element composition of melts from deep within their mantle source region (photo courtesy of N. Shimizu, WHOI)*

Particularly exciting is our increasing ability to analyze diverse chemical species on ever smaller sample sizes. We know that a wide range of melt compositions are produced within the melting regime that record the conditions under which each is generated, and yet the magmas erupted at the surface represent the pooled amalgamation of these instantaneous melts. Thus, much of the detailed information about conditions throughout the melting regime is averaged out. Melt inclusions, however, are often present trapped with phenocrysts and appear to record compositions closer to those of the instantaneous melts (Figure 2). With improved microanalytical techniques it is now possible to analyze not only the major element compositions of melt inclusions, but also their low abundance trace element and even Pb, Sr, Nd and possibly Hf isotopic compositions (e.g., by ion-microprobe or laser-ablation ICP-MS). Such studies confirm that the trace element and isotopic heterogeneity observed in melt-inclusions is frequently far greater than that observed in erupted melts. Interpretation of these melt-inclusions can be expected to provide important constraints on the lithologies and scale-lengths of mantle heterogeneities, as well as the diversity of melt compositions produced by variations in the extents, pressures and styles of melting within the melting regime and how these melts evolve en route to the surface.

A second exciting analytical approach is high-precision, high-sensitivity analysis of uranium-series nuclides. Recent improvements in the measurement of ^{230}Th, ^{226}Ra and ^{231}Pa by mass spectrometry have opened a wide range of new applications, and the advent of high-resolution ion-microprobe and laser ablation ICP-MS may soon revolutionize these analyses. Fractionation of U-series nuclides is particularly sensitive to the styles of melting and melt-transport, allowing a detailed perspective on these processes as well as mantle source characteristics. In principle, mantle upwelling and melting rates can be determined, distinctions can be drawn between batch, fractional or critical melting, and the nature of the plumbing system can be established (porous flow networks, focussed or fractal flow systems, etc.). Knowledge of these parameters is critical, for example, in determining the lithology of the mantle source and in understanding how plumes interact and are affected by ridge systems and surface plates. The problem of how melts are focussed into narrow linear zones at ridges may also finally be answerable with these tools. Another important application of U-series analyses is to the recalcitrant problem of dating of young ocean ridge lavas. U-series ages of the few dozen samples analyzed to date has identified with confidence, for example, those lavas that erupted off-axis (and thus tapped more distal portions of the melting regime). Further U-series dating studies of lavas from diverse ridge environments world-wide hold the promise of constraining the timing and episodicity of volcanism vs. tectonism as a function of spreading rate.

Our ability to decipher upper mantle processes through the chemical analysis of recovered samples obviously depends on the quality of the sample suite. Therefore, improvements in sampling techniques must go hand-in-hand with improvements in analytical approaches. With respect to ocean ridges, for example, a ‘reconnaissance’ sampling study of a decade or two ago might consist of at best one dredge every few kilometers. While this sampling strategy was sufficient to identify gross regional variations in average compositions, it is clearly inadequate to study processes that are manifest in the diverse range of melt compositions produced (e.g., diversity of instantaneous melts, small-scale mantle heterogeneities, differences in on-axis vs. off-axis lavas etc.). Furthermore, reconnaissance dredging, by its nature, is ‘blind’ with respect to geology (did the dredge sample several flows or a single flow?; did it sample the most recent or an older flow?). In addition to continued use of submersible sampling capabilities, there is increasing interest in the development and use of diverse detailed sampling technologies, ranging from transponder-navigated rock coring to remotely operated vehicles (ABE, Jason, or Tiburon). The use of such tools is opening a new era in the study of oceanic volcanism in which geochemical and geophysical constraints can be understood within a geological context that may one day approach the kind of information we have for on-land investigations.

3.3 Advances in Geodynamical Modeling

Theoretical and numerical modeling studies provide predictions of the observable consequences of complex physical processes that can be tested against observations and provide the basis for design of new experiments. Observations can then be used to reject the physical assumptions on which the model is based or refine them. In the earth’s mantle, where structure can only be observed remotely, no geophysical or geochemical experiments can ever provide enough information to uniquely constrain the dynamic processes. Geodynamic modeling must fill the gap by constructing models that both satisfy the data and obey our current understanding of the physics and chemistry of the earth. Recently, major advances in geodynamic theory and modeling have occurred in response to 1) a growing understanding of appropriate theoretical descriptions of complex processes such as melting and solid state creep, 2) improved numerical methods for creating quantitative models incorporating these theoretical descriptions, and 3) tremendous increases in the affordability, speed, memory and data storage capacity of computer systems.

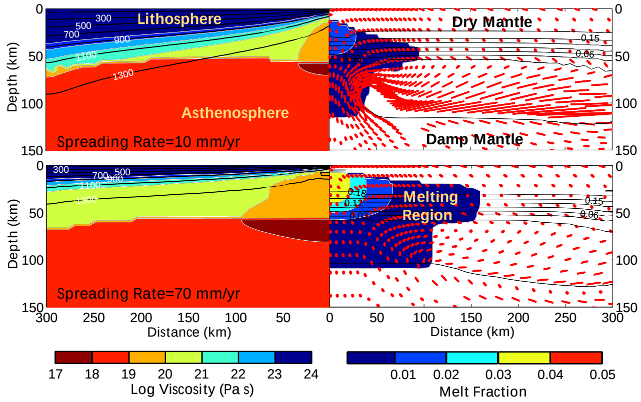

Figure 3. *Numerical models incorporating more realistic rheologies and the effects of water predict systematic variations in the size and shape of the melting region, the importance of buoyant flow, and the degree of flow-induced anisotropy that can now be directly tested by seismological and other geophysical and geochemical observations (from Braun et al., 2000).*

On a global scale, the first self-consistent, three-dimensional models of mantle convection that include plate motion have recently been developed. Previously, the geometry of plates had to be prescribed, i.e., inserted by hand, because the temperature-dependent, viscous creep representation of mantle rheology employed in the models did not permit the natural development of lithospheric plates. Instead, a rigid, globally continuous lid developed at the cold surface of the earth. Numerical experiments with more complex rheologies, including finite yield strengths and strain weakening are beginning to exhibit true plate-like behavior developing from the basic driving forces of convection. More realistic, global models are being developed that invoke distributions of anomalous density based on seismic tomography and satisfy observations of the geoid and surface topography of the earth. These models make predictions of the internal structure of the earth that can be tested by acquisition of higher resolution seismic images of the earth and more complete global coverage.

Important advances have also come from regional or local models of mantle dynamics. The processes leading to localization of strain on faults or at plate boundaries require extremely high resolution and are best treated with local models. Small-scale convection in the asthenosphere or flow induced locally at plate boundaries is difficult to represent in global models, but have been successfully developed in regional models. New models are being constructed of two-phase flow that describe the separate paths of melt and mantle matrix and the geochemical consequences of the separate paths of these two very different “fluids”. Recently, models have incorporated our knowledge of the slip systems of crystals to predict the anisotropic, crystalline fabric that develops during mantle flow (Figure 3). The predicted fabric, in turn, can be tested against observations of seismic anisotropy, such as shear wave splitting and azimuthal variations in velocity. As information about the physical properties of mantle materials and solid/melt systems increases, it is being incorporated in ever more detailed predictions of geophysical and geochemical observables.

Modeling capabilities are also rapidly improving for seismic and electromagnetic wave propagation in three-dimensional, anisotropic, heterogeneous media. As the density of station coverage increases in magnetotelluric and seismic tomography experiments, more of the waveforms can be exploited. However, understanding this additional information requires more complete and accurate representation of wave propagation than previously available. New algorithms and more powerful, massively parallel computing systems are just beginning to put realistic, 3-D models within the realm of possibility. In the next decade, there will be explosive development of this field, eventually linking 3-D geodynamically modeling with fully 3-D representation of wave propagation.

4.0 Results From Recent Seismic Experiments

LABATTS (Lau-Basin Tonga Trench Seismic) Experiment

The 1994 LABATTS experiment represents a prototype arc-backarc experiment. It consisted of 12 land broadband island stations and 30 1-Hz ocean bottom seismographs, deployed for 90 days. P-wave tomography with the LABATTS dataset clearly shows slow upper mantle velocity regions associated with the backarc spreading center and the magmatic arc (Figure 4), as well as showing a complex pattern of mantle flow, as indicated by shear wave splitting observations (Figure 5). Resolution was limited by the 2-D nature of the main array and the ~ 50 km station spacing; further improvements in understanding the pattern of mantle flow can be obtained with a larger array of broader band OBSs deployed for a longer time yielding higher resolution images. Nevertheless, as described below, some major advances were made.

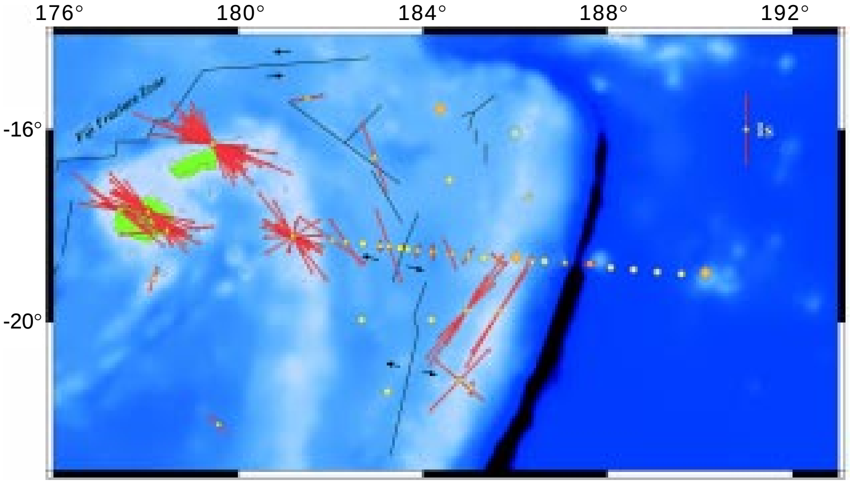

***Figure 5**. Shear wave splitting observations from the LABATTS experiment (*Smith et al, *in prep.). Arrows denote the fast splitting direction, and arrow lengths represent the magnitude of the splitting. The Lau basin anisotropy suggests a complex pattern of mantle flow in the backarc.*

Seismic tomography using teleseismic, local, and OBS arrivals clearly images a slab with velocity 6% faster than the surrounding mantle (Figure 4), and suggests that slow velocity anomalies extend to depths of 400 km beneath the backarc spreading center. Attenuation tomography using regional waveforms shows a low Q zone beneath the Lau spreading center. Comparison of attenuation and velocity tomographic images provides an empirical relationship between V and Q that is consistent with lab results.

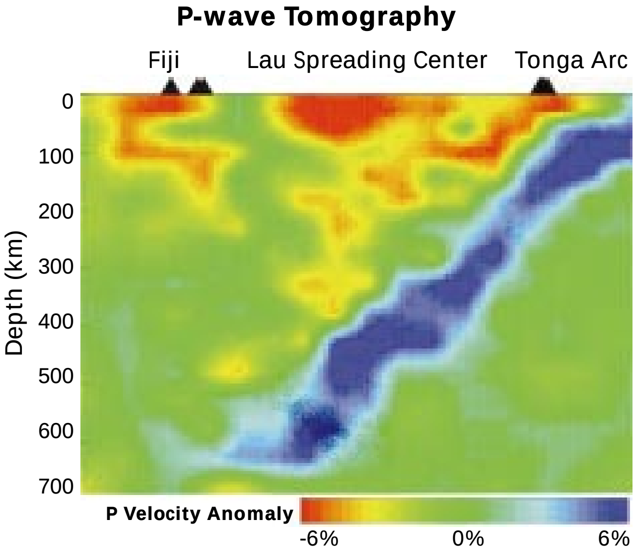

***Figure 4**. Seismic tomographic image of P-wave velocity anomalies across the Tonga arc and Lau backarc, from the 1994 LABATTS experiment (*Zhao et al.*, 1997). Slow velocity anomalies (denoted by red colors) are observed beneath the Tonga volcanic arc and Lau spreading center. Fast velocities (blue colors) show the subducting Pacific plate.*

Regional waveform inversion suggests upper mantle velocity heterogeneity of up to 16% between adjacent tectonic regions, with exceptionally slow seismic velocities in the backarc basins, extending to depths of about 180 km. P/S anomaly ratios suggest these anomalies result largely from temperature variations rather than the presence of partial melt. Forward modeling of the slab travel-time anomaly using thermal and petrological models for the Tonga slab suggest that the anomaly can be well fit by simple thermal models and accepted values of DV/DT. Initial results show little evidence of a metastable olivine wedge. Aftershocks of a large, deep earthquake beneath the array show that rupture zones can extend outside the active Benioff zone, suggesting that models of deep earthquake occurrence through transformational faulting within a metastable wedge are too simplistic.

Shear wave splitting along paths from deep events to Fiji show ~1.5 s splitting, with fast axes parallel to the convergence direction at the trench. Inversion of local paths and teleseismic *SKS* results show that azimuthal anisotropy is limited to the upper 400 km. Analysis of splitting from OBS stations shows a complex pattern of splitting in the backarc (Figure 5), possibly due to southward flow from the Samoa hotspot into the mantle wedge region. Multiple ScS phases that interact with the 400 km and 670 km discontinuities suggest that the 670 km discontinuity is depressed by 20-30 km in the region of the Tonga slab.

MELT (Mantle Electromagnetic and Tomography Experiment)

The MELT Experiment was designed to distinguish between competing models of magma generation in the mantle beneath mid-ocean ridges. In some ways, it serves as a model for future projects as it was the first major experiment to deploy arrays of seismometers, electrometers and magnetometers on the seafloor for periods of six months or more. The experiment demonstrated that the wide spectrum of tools of earthquake seismology could be employed to study processes in the mantle and that seismic, electromagnetic and other geophysical and geochemical approaches could be coordinated to provide complementary information. The MELT Experiment is proving to be a tremendous scientific success, but it also points to the importance of the development of instrument pools, both to increase efficiency and to reduce the problems of intercalibration of instruments of different design. Both the seismic and electromagnetic deployments involved instruments from four different research groups, multiplying logistical difficulties and increasing the cost. Initial results from the MELT Experiment were presented in a series of papers in *Science*, and are summarized briefly below.

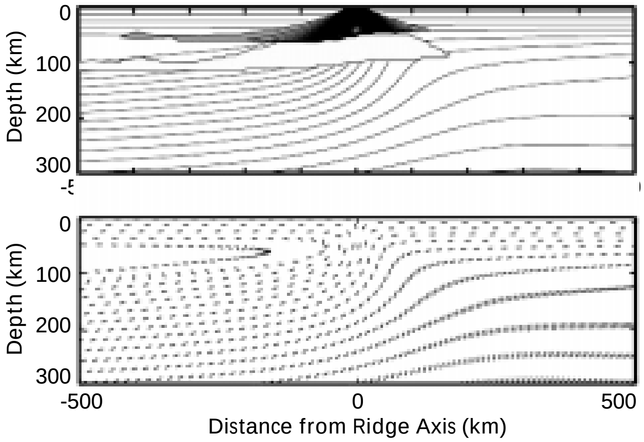

Figure 7. *Possible streamlines in the mantle in the MELT area (in the ridge-fixed coordinate frame). Upper figure shows predicted areas of melt production if there is a thermal anomaly introduced into the asthenosphere from the Pacific superswell to the west, with light grey indicating melting below the dry solidus and darker shades, melting above the dry solidus. Lower figure shows directions of alignment of maximum principal axis of finite strain, which may be responsible for asymmetry in shear wave splitting. (after* Toomey et al., *2000)*

At mid-ocean ridge spreading centers, the separation of the plates induces upwelling in the underlying mantle to fill the gap and to replace the mass in the asthenosphere dragged away from the ridge by the motion of the plates. Partial melting of the upwelling mantle generates the magma that forms new crust at the ridge axis. The pattern of upwelling, the lateral and vertical extent of the melting region, and the pathways of melt delivery to the ridge crest are not well known and were the primary targets of the MELT Experiment. Geochemical and petrological data indicate that most of the melt is produced at depths shallower than 60 km, but that there is likely to be some contribution from greater depths within the garnet stability field. The passive upwelling caused by drag of the plates is likely to be broad, inducing melting in a region that may be 100 hundred km or more wide. If much melt is retained in the mantle matrix, however, it provides buoyancy and locally reduces viscosity, allowing a dynamic or buoyant component of convection to develop, which could concentrate upwelling and melting into a narrow region, perhaps less than 10 km across.

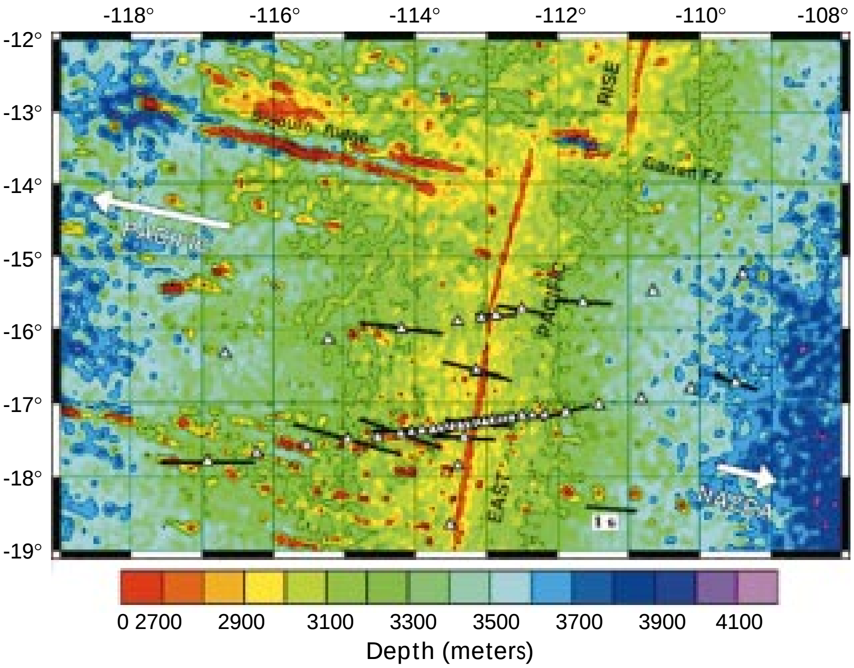

Figure 6. *Layout of the MELT Experiment. Contours and colors show bathymetry, white arrows show plate motions in hotspot frame, triangles are locations of OBSs, black bars indicate degree and fast direction for shear wave splitting. (after* MELT Seismic Team, *1998 and* Wolfe and Solomon, *1998).*

The MELT Experiment found no evidence for a narrow region of high melt concentration that would indicate focussed upwelling. Instead, a broad region of low velocities was found at depths of 30 to 60 km, suggesting that passive upwelling may dominate the flow pattern. The mantle structure

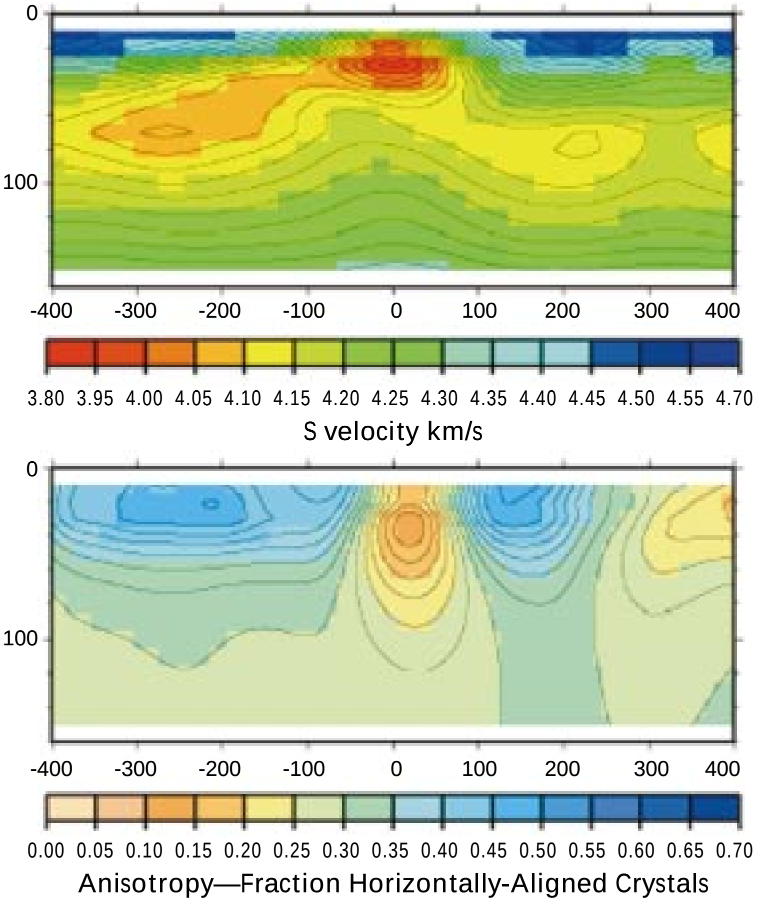

Figure 8. *Cross-section through the ridge axis of shear wave velocity (top) and alignment of olivine crystals (bottom) based on inversion of Rayleigh wave velocities observed in the MELT Experiment. Note more vertical alignment near the ridge axis (0 km on horizontal scale).*

proved to be surprisingly asymmetric. The seafloor subsides more rapidly to the west of the ridge axis on the Pacific plate than to the east on the Nazca plate (Figure 6). Shear wave splitting changes abruptly across the axis from nearly two seconds on the west to about half that value on the east (Figure 6). Because the shear wave splitting is caused by propagation through a layer with anisotropic crystalline fabric generated by mantle flow, this asymmetry suggests there is a fundamental asymmetry in mantle flow. The probable cause of this asymmetry is the migration of the spreading center relative to the underlying deep mantle. The Pacific plate is moving to the west at about 101 mm/yr, while the Nazca plate moves to the east at about 45 mm/yr in the hotspot coordinate system. This asymmetric motion creates predictable variations in strain in the mantle (Figure 7) that we can model and compare to the observations.

Asymmetry is also found in seismic wave velocities and electrical conductivity. At depths of about 45 km, very low shear velocities indicative of the presence of melt extend more than 200 km to the west of the axis, but disappear within 100 km to the east. A cross-section perpendicular to the ridge shows that the shallower structure is more symmetric and that there is an apparent change in anisotropy beneath the ridge axis that may be associated with upwelling of the mantle (Figure 8). Both anisotropy and an asymmetric distribution of melt may contribute to the asymmetry of the electrical resistivity structure. Modelling of magnetotelluric data from the MELT Experiment indicates that the resistivity immediately to the east of the axis is characteristic of dry, melt-free peridotite, while to the west, there may be some interconnected melt present. The change in resistivity may also be affected by the more vertical alignment of olivine crystal a-axes just to the east of the ridge axis.

SWELL (Seismic Wave Exploration in the Lower Lithosphere)

The SWELL experiment was a pilot study designed to show the feasibility of using intermediate-period (15-80s) Rayleigh waves recorded by ocean bottom instruments to study upper mantle structure beneath a mid-plate hotspot swell. The principal scientific motivation for this experiment was to characterize the interaction between the plume and the lithospheric mantle, in particular to address the origin of hotspot-related bathymetric swells. Eight SIO L-CHEAPO instruments with differential pressure gauge (DPG) sensors were deployed at ~200 km station spacing in a hexagonal array with the center being roughly 375 km to the south-west of Big Island/Hawaii (Figure 9a). Two instruments were located at the central site, at a separation of about 25 km, to guarantee the full lateral resolution of the array should one instrument fail. The array extended across the width of this part of the swell and encompassed the Ocean Seismic Network pilot borehole seismometer installation at ODP Site 843B. The instruments were deployed for a total of 12.5 months with one recovery/re-deployment cruise after the first 7.5 months.

The collected surface wave records include high-quality waveforms from 84 teleseismic shallow events that were well distributed in azimuth (Figure 9b). For most of the 84 events, dispersion could be measured between periods of 17 and 50 s; the high quality of the waveforms for some events allowed these measurements to be extended to 70 s or beyond. The analysis provided over 50 dispersion curves with errors bars small enough to reliably distinguish between different lithosphere-asthenosphere velocity models. The good azimuthal coverage of events also constrained upper mantle anisotropy beneath the array and permitted an unbiased estimate of the average isotropic seismic structure beneath the pilot array to be obtained. The average azimuthally isotropic structure beneath the array is very similar to that of 90-My-old lithosphere. The average amount of azimuthal anisotropy is rather modest; no greater than

2% at periods of 30-60 s. The direction of fast phase velocity follows the current plate motion direction for periods longer than 40 s and tends toward the fossil spreading direction for shorter periods. This is in accordance with a two-layer anisotropic model in which flow induced by plate shear dominates anisotropy in the asthenosphere and anisotropy aligned with the fossil spreading direction is 'frozen' into the lithosphere.

More interestingly, there is clear evidence for a strong lateral gradient in structure across the array. Phase velocity maps obtained by measuring the dispersion between each two-station leg of the pilot array, as a function of period, suggest small changes at short periods but at periods greater than 35 s there is a pronounced velocity gradient perpendicular to the island chain, with anomalously low velocities close to the islands. Inversions of the phase velocity maps reveal a moderately deep swell root that is restricted to be close to the island chain (Figure 9d). These results demonstrate clearly that surface wave tomography carried out with a larger network can resolve the deep structure of the Hawaiian swell.

Modelling of the seismic velocities found near the island chain suggest that most of the low seismic anomalies may be caused by purely temperature effects, but the presence of a small fraction of partial melt (<2%) cannot be ruled out. The seismic pilot deployment also included a co-deployment of 8 MT instruments. This study found no increase in electrical conductivity near the islands as would be expected if significant fractions of connected partial melt were present (Figure 9c). This is further evidence that most of the anomaly seen in the seismic signal must be caused by elevated temperatures in this area.

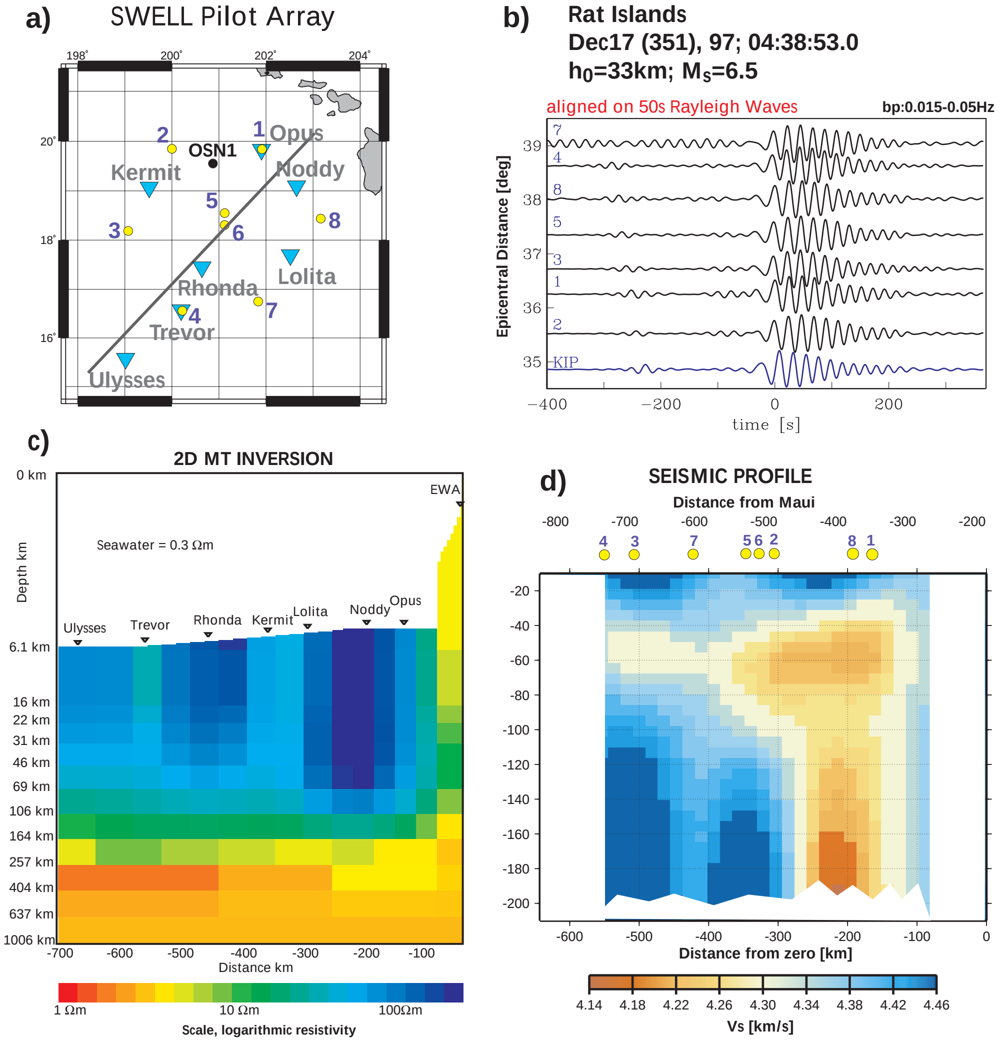

Figure 9. *a) Site map of the SWELL Pilot array (*Laske et al.*, 1999). Numbers mark seismic sites, while names mark the MT sites. The OSN1 test borehole site is also marked. b) Example of SWELL seismic data for a Rat Islands event. The blue trace is the vertical record from GSN station KIP (Kipapa, Oahu). The KIP seismogram is not corrected for instrumental response or converted to pressure. All records have been bandpass filtered. c) 2D MT resistivity model and (d) 2D profile through 3D seismic shear velocity model obtained across the SWELL pilot array (line indicated in map in (a)).*

5.0 Examples Of Possible Projects

The following examples of experiments that might be executed under the aegis of the OMD Initiative are meant to be illustrative of projects that would advance our understanding of the dynamics of the oceanic upper mantle using the new national OBS Instrument Pool, and would involve collaboration between geophysicists and petrologists or geochemists. Some projects might use OBSs in a passive mode, recording local or teleseismic earthquakes. Others might employ OBSs in an active experiment with artificial sound sources. Some might involve a field component of sampling rocks followed by laboratory analysis or a field component of some other type of geophysical measurement such as electromagnetic depth sounding. Not every experiment would have to involve all aspects, but all would include petrologists, geochemists, and geodynamicists in the ultimate interpretation. The list below is not meant to be all-inclusive or to necessarily indicate that all these experiments are higher in priority than others that might be proposed.

Intraplate swell/hotspot experiment (G. Laske)

Hotspots are widely believed to the surface manifestation of buoyant plumes rising from the lower mantle. As such, they are a fundamental part of the earth's heat engine. Hotspot volcanism provides the most direct evidence that the Earth's mantle is chemically, isotopically and thermally heterogeneous. This heterogeneity is maintained despite convective mixing, possibly due to the input of subducted material into the lower mantle. Although the mantle plume concept was first proposed by Morgan nearly 30 years ago, many fundamental questions still exist regarding mantle plumes and plume-lithosphere interactions.

- do plumes originate in the lower mantle or in the transition zone between the upper and lower mantle?

- what are the dimensions of plumes in the asthenosphere? Are they relatively broad (>200 km wide), warm (50-100°C) upwellings or a narrower (<100 km wide), hotter (200-300°C) pipe-like features?

- what is the depth of magma generation beneath hostpots and the lateral distribution of melt in the upwelling mantle?

- what is the relationship between the plume conduit and the surface expression of volcanism?

- are hotspot swells isostatically supported by reheating and thinning of the oceanic lithosphere or by the ponding of low-density mantle residuum at the base of an effectively normal-thickness lithosphere?

- does the horizontal flow of hot asthenospheric material that is sheared by the overlying plate play a significant role in forming swells?

While global seismic tomography studies of the Earth's mantle have made great strides in the last few years, the resolution of global and large-scale regional models is still insufficient to discern confidently the details of features such as plumes with dimensions of a few hundred kilometers or less. Land-based investigations of oceanic hotspots are also handicapped by the relatively small size of hotspot islands which severely limit the aperture of these experiments and hence their ability to resolve structure at depth or over broad areas around the hotspot. The modern ocean bottom seismic instrumentation that will be available through OBSIP will allow the powerful broadband seismic techniques developed by seismologists over the past two decades

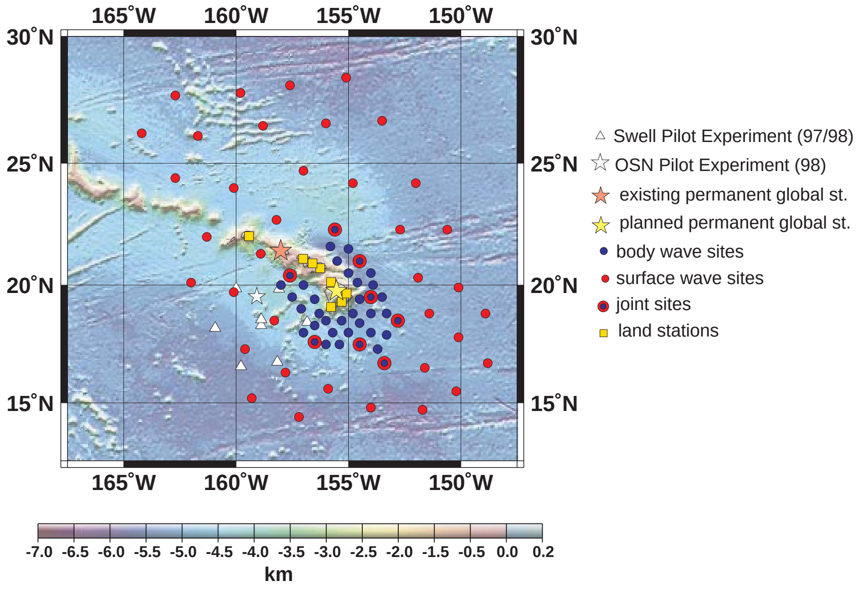

Figure 10. *Location map and network design for the PLUME experiment. The Hawaiian swell is the region of shallow bethymetry (light blue) extending roughly 500km to the north and south of the Hawaiian chain. Shown are locations of the proposed OBS sites for both the body wave and the surface wave tomographic studies. Shared sites are marked separately. Also shown are the locations of the proposed land-based instruments, the previous SWELL pilot experiment sites, the OSN-1 site, and stations of the permanent Global Seismic Network.*

to be extended into the oceans. Delay times of teleseismic P and S body waves can be used to construct three-dimensional images of upper mantle structure beneath oceanic hotspots and determine the location of the plume conduit, its width, and the magnitude of the thermal anomaly and any melt anomaly associated with the plume. Shear-wave splitting anomalies can be used to constrain flow-induced alignment of olivine grains in the mantle beneath oceanic hotspots, and thus determine the pattern of plume upwelling and mantle flow in the asthenosphere as well as any fossil anisotropy in the lithosphere above. Receiver function analyses can be used to determine if there is a decrease in upper mantle transition zone thickness beneath hotspots which would be indicative of a lower mantle origin for plumes. Intermediate-period surface waves (15-80s) can be used to characterize the interaction between the plume and the upper mantle and address the origin of the hotspot-related bathymetric swells. An important component of any plume imaging seismic experiment will be the integration of new seismic constraints with geochemical and geodynamical constraints on upper mantle dynamics. For example, temporal variations in eruption rates, major and trace elements, and isotope studies have been used to estimate the location, size, and temperature of plumes. However, these estimates are highly uncertain and model-dependent. A direct determination of the lateral extent of a plume at depth in the mantle will provide critical ground truth for these models.

An example of the design of an intraplate/hotspot swell experiment is the Plume-Lithosphere Undersea Melt Experiment (PLUME) (Figure 10). The goal of PLUME is to image the seismic structure of the Hawaiian plume conduit and a major part of the Hawaiian swell. This experiment would include 64 ocean-bottom seismic instruments and 10 portable broadband seismic instruments on the islands deployed for a 15-month period. An inner subnetwork of 24 four-component, intermediate-band OBSs plus the 10 broadband land stations is designed primarily to image the plume conduit by means of body wave tomography. Inter-station spacing within this subnetwork is approximately 75 km. An outer subnetwork of 39 instruments is designed for surface wave tomographic imaging of the lithosphere and asthenosphere beneath the surrounding swell. Eight of the 64 seafloor instruments are joint sites for both the body-wave and surface-wave tomography portions of the PLUME experiment.

Ridge-hotspot interaction – off-axis hotspot (G. Ito)

Of the 30-50 hotspots that are thought to be surface expressions of convection plumes arising from the deep mantle, at least 17 have documented chemical and physical influences on mid-ocean ridges. The total length of affected ridge axis amounts to roughly 20% of the entire global midocean ridge system. In addition, the presence of large volcanic ridges such as the Walvis and Rio Grande Rise in the south Atlantic; giant igneous plateaus such as Kerguelen in the Indian Ocean; and bathymetric swells that, in some cases such as in the North Atlantic, extend over whole ocean basins indicate that plume-ridge interaction has been prominent throughout the recent geologic history. Thus the interaction of Earth's two dominant modes of mantle upwelling appears to be an important process that shapes the structure and alters the composition of the oceanic lithosphere and crust.

That an upper mantle plume can flow against the drag of a migrating plate and feed material to a ridge axis, sometimes over distances of several hundred km, is a challenging hypothesis that has puzzled earth scientists for the past ~30 years. Still, the structural and chemical evidence for such interaction is indisputable. An example is illustrated in Figure 11. In this bathymetric map of the eastern Pacific, the Galapagos Spreading Center comprises a ~1000-km-broad bathymetric anomaly. The ridge axis lies ~200 km north of the Galapagos hotspot which is currently erupting at the Galapagos archipelago. Closely correlating with the long-wavelength bathymetric swell are gradients in magma composition that reflect variations in melting and mantle source composition as a function of distance away from the hotspot. In addition, two prominent volcanic ridges extend away from the hotspot and record magmatic productivity of plume-ridge interaction over several tens of millions of years. The Galapagos plume-ridge system is an archetypal example of a ridge interacting with an off-axis hotspot. Other plume-ridge systems often exhibit some of the same general physical and geochemical characteristics.

Many hypotheses and conceptual models have evolved over the past 30 million years related to fundamental questions of the upper mantle dynamics of a ridge interacting with an off-axis plume:

- How does an off-axis plume feed material to a nearby, or even distant, midocean ridge? How is mantle material then transported along the ridge axis? Is this flow through relatively confined, pipe-like channels or does transport occur over broad, more diffuse flows?

- What causes the observed gradients in geochemical source signatures along plume-influenced ridges? To what degree does the apparent source mixing occur by stirring of plume and ambient mantle in the solid state, versus mixing of melts? What do lateral gradients in source composition tell us about the chemical structure of mantle plumes and thus mixing processes in the deep mantle?

- How does melting change along a plume influenced ridge? How does the melting zone vary in lateral and vertical extent along-axis, as well as between the hotspot and ridge? To what degree does melt productivity change along axis? What are the feed back mechanisms between melting and mantle flow?

- What is the temporal variability of melt productivity and composition? To what degree does temporal evolution reflect deep-seated changes in the plume source, variations in plume-ridge separation, and changes in ridge geometry. Why does plume-ridge interaction appear to promote the initiation of new ridge segments and cause existing segments to propagate?

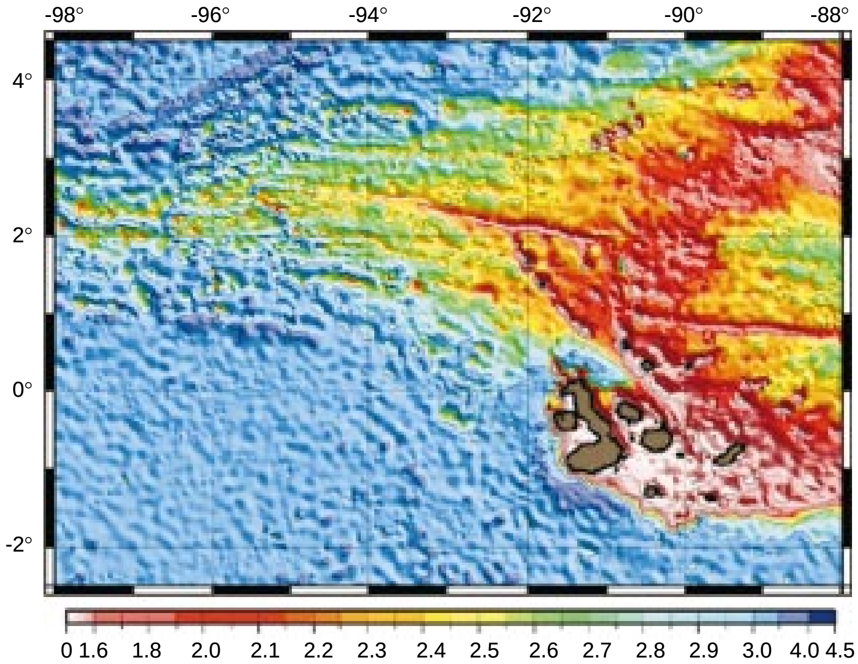

Figure 11. *Satellite-derived bathymetry (*Sandwell and Smith, *1997) for the Galapagos region illustrating the bathymetric expression of plume-ridge interaction in this area*

With the new capabilities of marine seismology to image mantle seismic properties at increasing resolution, more sophisticated methods of geochemical analysis to constrain source and melting properties, and advanced computational power necessary for a high resolution numerical models, we are well poised to make exciting progress in addressing the above questions. By nature of these questions, they can be adequately addressed only with multi-disciplinary studies that integrate geophysical observations, geochemical measurements, and quantitative modeling.

A number of field programs and theoretical modeling efforts can be envisioned. The problem of mantle flow to a ridge axis, for example, will require seismological imaging of a region of mantle at least as broad as the extent of volcanism off axis, and approaching the extent of the bathymetric swell along-axis. Theoretical models will then be needed to use the seismological constraints to quantitatively examine the possible driving mechanisms. The problems of along-axis mantle flow, lateral variations in melting, and mantle source mixing are intimately related. For example, in order to separate mantle source variability from variations in melting, independent constraints on magma productivity are needed. It will therefore be necessary to obtain constraints on variations in crustal thickness (i.e., magmatic productivity), with coincident measurements of basalt chemistry. In addition, models existing to date, predict testable relationships between the pattern of melt production rate and different styles of along-axis transport of plume material. Such melting patterns can be constrained by integrating information on the variability in crustal thickness and variations in mantle seismic properties. Furthermore, geochemical methods using short-lived radionuclides are showing increasing promise in providing additional constraints on melting rates. Finally, the problem of source mixing can be well addressed with geochemical sampling at high spatial resolutions combined with geochemical and geodynamic models that include processes of mantle flow as well as melt transport.

To maximize the scientific gains of the above types of studies, several factors must be considered in selecting a study site. Firstly, it will be important to choose a plume-ridge system with a geographic extent small enough that experiments can feasibly encompass the region with sufficient resolution. Secondly, the site will need adequate existing coverage of bathymetric and geochemical data so that the primary geological features and extent of the hotspot anomalies are reasonably well defined. Thirdly, we will seek a ridge with a simple geometry and a hotspot with a well established history of robust volcanism. Finally, the seismic programs will require an adequate frequency and azimuthal distribution of teleseismic sources, as well as minimal sea noise levels. The Galapagos plume ridge system meets each of the above requirements to various degrees. This system is therefore an excellent candidate site in which to hold a series of integrated studies designed to address specific questions regarding plume-ridge interaction.

Ridge-hotspot interaction – on-axis hotspot (Y. Shen)

A ridge-centered hotspot is a special case of the more general problem of plume-ridge interaction. Ridge-centered hotspots are particularly important because they are responsible for the formation of many large aseismic ridges and volcanic plateaus found throughout the ocean basins. They also provide the most direct thermal, chemical and dynamical perturbation to the normal mid-ocean ridge spreading process. Iceland is a classic example of ridge-centered hotspots. The relatively large area of the island and the short distances to the adjacent islands and the Atlantic coasts make Iceland ideally situated for

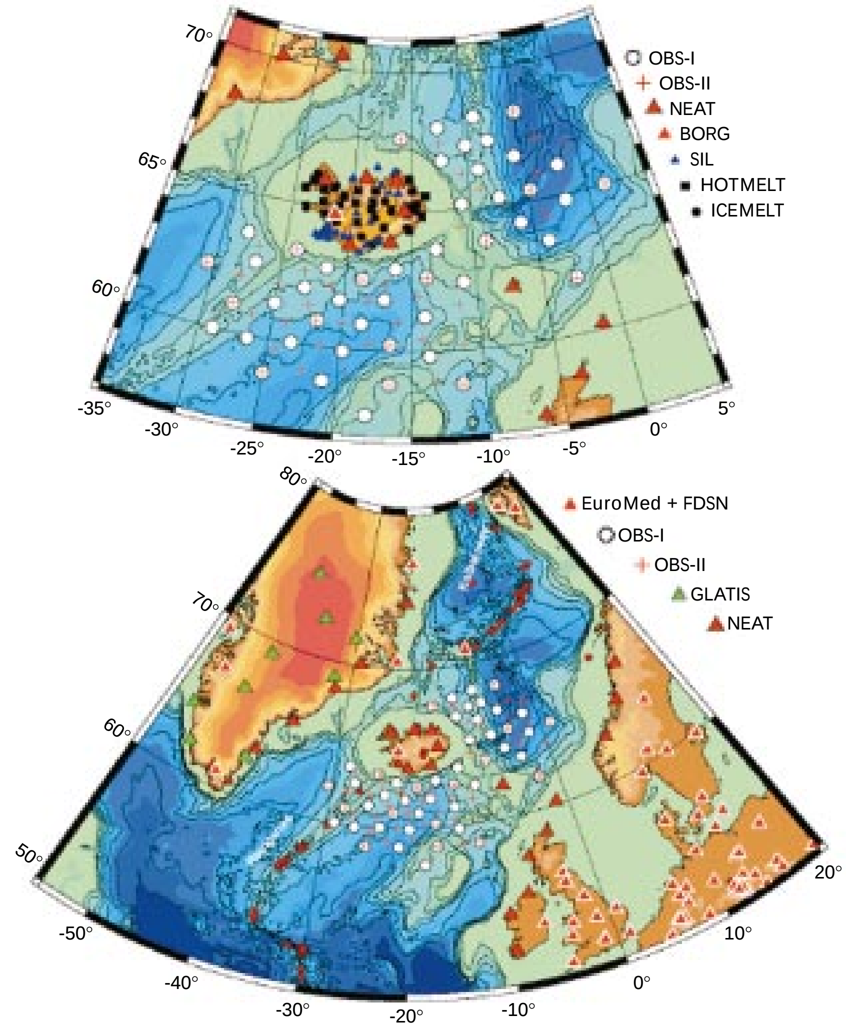

Figure 12. *A possible Iceland ridge-centered plume seismic experiment.*

a combined OBS and land-based seismic experiment to obtain a complete picture of a ridge-centered plume in the upper mantle and the uppermost lower mantle. Several important questions can be addressed with observations of the mantle structure beneath a ridge-centered plume from an array of ocean-bottom seismometers (OBSs) and constraints from petrology, geochemistry and theoretical modeling of geodynamic processes:

- *From what depth do mantle plumes originate?* While an upper mantle origin of mantle plumes indicates layered mantle convection and the associated chemical layering, plumes rising from the lower mantle suggest whole mantle convection and mixing.

- *How do mantle plumes interact with the mantle transition zone?* The penetration of mantle plumes through the upper-lower mantle boundary occurs under certain conditions related to the Clapeyron slopes of the phase changes near 410 and 660 km depth. Thus observations of the interaction between plumes and the upper mantle transition zone provide constraints on the physical properties of the phase changes.

- *What is the radius of the mantle plume? Does the radius of the plume conduit vary with depth?* The depth dependence of the width of the plume conduit provides constraints on the mantle viscosity structure, because an increase in viscosity in the lower mantle would require a wider plume conduit to maintain the same flux of material.

- *How does the plume mantle spread beneath the lithosphere?* Many models have been developed for plume-ridge interaction and particularly for flow away from Iceland in the asthenosphere along the Reykjanes Ridge. Observations of the structure beneath Iceland and the adjacent ridges will provide constraints to distinguish the competing models.

Several attempts have been made to image a mantle plume in Iceland. Using a global data set, one group reported a low-velocity anomaly continuing across the 660-km discontinuity beneath Iceland extending all the way to the core, others suggested that the low velocity anomaly beneath Iceland is confined to the upper mantle. At regional scales, travel times of teleseismic body waves recorded by 15 broadband seismic stations in the ICEMELT experiment found a cylindrical zone of low velocities that extends from 100 km to at least 400 km beneath central Iceland. The tomographic images fade at near 400 km depth because stations on Iceland cannot see wave paths cross much below 400 km. Shear waves that converted from P waves at seismic discontinuities, show that the transition zone between the 410- and 660-km discontinuities is 20 km thinner beneath central and southern Iceland, indicative of a lower mantle origin of the Iceland plume. The HOTSPOT experiment deployed about twice as many broadband seismic stations as in ICEMELT, but the problem of the lack of crossing rays at depth greater than 400 km remains, leaving the controversy about the depth of origin of the Iceland plume unresolved. Given the contradicting results, it is clear that a strong inference of the depth of origin of the Iceland plume requires images of well-constrained seismic velocities in the mantle transition zone and the uppermost lower mantle beneath Iceland. The needed measurements cannot be gathered from the Iceland stations, but can be obtained with offshore OBSs.

A possible design of an seismic experiment at Iceland that includes both existing land-based seismic stations and ocean bottom seismic stations is shown in Figure 12. The combined data would come from 48 OBSs in two successive summer seasons (when the weather is calmer), the broadband seismic stations in ICEMELT and HOTSPOT, the SIL network operated by the Icelandic Meteorological Center, portable broadband stations along the Atlantic coasts, and the permanent broadband seismic stations in the region. The OBSs are placed to maximize recording of seismic arrivals that pass through the plume beneath Iceland and resolving the deep structure of the plume. No OBSs are deployed west of Iceland because of drifting ice in late spring and fall. Previous OBS experiments in the Atlantic showed that high-frequency (>0.5) seismic waves, which are critical to imaging a narrow low-velocity plume at depth, can be recorded. Two summer recording seasons would be needed to record enough high-frequency signals for a well-constrained 3-D velocity structure. The second deployment would reoccupy 1/3 of the sites in the first deployment for site specific analysis such as shear-wave splitting and receiver function studies. The remaining stations in the second deployment would be shifted to yield a combined station spacing of 60-70 km and an evenly distributed ray paths in the same volume of mantle.

The combined stations would have an aperture of ~ 1400 km by 1500 km and could image the Iceland plume in the upper 900 km with crossing rays. Regional earthquakes recorded at Jan Mayen, Spitzburger and along the Greenland coast would provide shallow incidence rays in the upper mantle transition zone and the uppermost lower mantle beneath Iceland. With careful waveform modeling for triplications [*Grand*, 1994], those regional arrivals can be inverted simultaneously with teleseismic data and will significantly improve vertical resolutions in the transition zone and the uppermost lower mantle. Surface wave analysis must be an integral part of tomography. The shallow structure not resolved by body waves will be resolved in part by surface waves. The lateral heterogeneity near the surface under the OBSs can be accurately mapped using waveform fitting from oceanic events. The crustal thickness can also be constrained using receiver functions. Portable broadband seismic stations are important for this purpose because they record longer period (20-120 s) surface waves and ensure deep enough resolution for the whole region.

Intraplate volcanic ridges and small-scale convection (D. Forsyth)

There are intraplate, volcanic ridges on the Pacific plate whose origin is not well understood. The best known is the Puka-Puka set of en echelon volcanic ridges which extends for 2600 km from young sea floor west of the East Pacific Rise to near Puka-Puka atoll south of the Marquesas. Their origin seems to be linked to equally enigmatic gravity lineations that are aligned in the direction of absolute plate motion. Although they have not been thoroughly investigated, it has been demonstrated that these ridges are not hotspot traces, they do not form in the near-ridge, spreading environment, and they are not volcanic arcs in a subduction setting. Suggestions for their origin include small-scale convective rolls in the asthenosphere, lithospheric boudinage or stretching (Figure 13), and small plumes resembling mini-hotspots that originate in the upper mantle. Whatever their origin, these ridges and the gravity lineations provide one of the few clues to the mantle processes in the vast intraplate region between plate creation at the spreading centers and subduction of the plates at trenches.

One of these sets of intraplate volcanic ridges, the Hotu-Matua system, is currently actively building and extending, as revealed by side-scan sonar imaging of recent lava flows. A detailed seismological, geochemical and geophysical study of the Hotu Matua complex and the adjacent Sojourn intraplate ridge (Figure 14), should make it possible to distinguish between the competing hypotheses for their origin. In particular, the experiment should be able to address the following questions:

- *Is there thinning of the crust associated with lithospheric extension beneath the ridges?*

- *What is the distribution of fresh lava flows?*

- *What is the effective elastic thickness of the lithosphere?*

- *What are the depths and focal mechanisms of microearthquakes at the propagating end of the ridge system?*

- *What is the distribution of melt in the mantle beneath the volcanic ridges?*

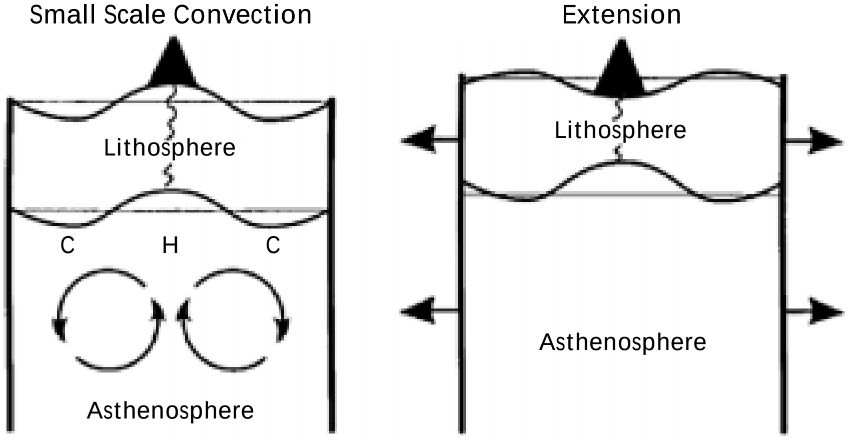

Figure 13. *Schematic illustrations of two of the models suggested for the origin of intraplate, non-hotspot ridges (from Sandwell et al., 1995). Melting occurs above upwelling zones, either in the limb of a convective cell or where the lithosphere thins as it stretches.*

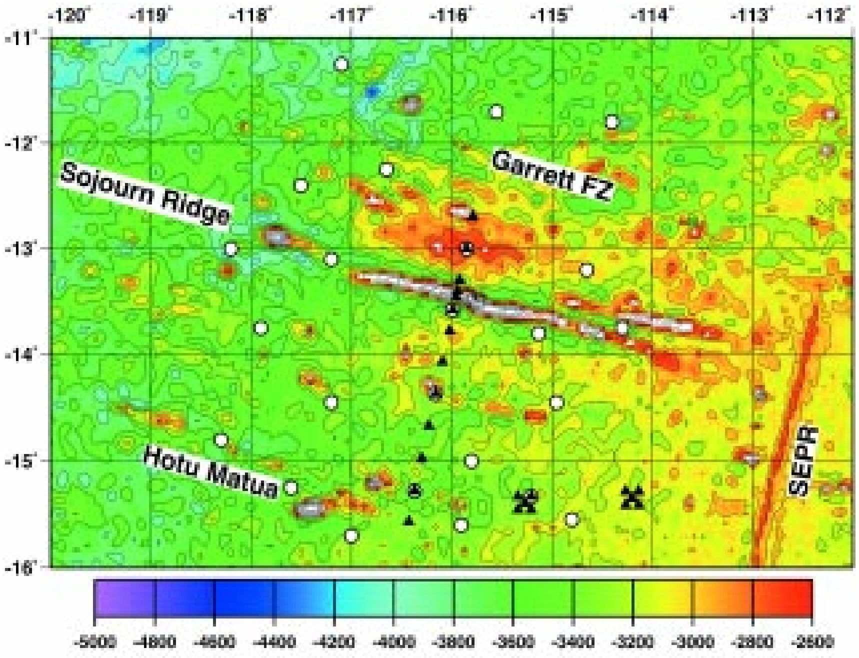

***Figure 14**. Design of an OBS experiment to study upper mantle processes beneath the Sojourn and Hotu Matua, intraplate, volcanic ridges. SEPR is southern East Pacific Rise. Triangles indicate short-term deployments of OBSs for refraction or microearthquake studies, circles long-term deployments for passive seismic tomography.*

- *What is the depth extent and degree of partial melting?*

- *Does melt production involve progressive melting of the partially depleted, residual layer formed at the East Pacific Rise?*

- *What is the age progression along the volcanic ridges?*

Active arc-backarc system (D. Wiens)

An active arc-backarc system juxtaposes the major processes of the plate tectonic cycle within a rather small geographic region, and thus represents an optimal location for a major broadband ocean bottom seismic experiment. An arc-backarc seismic experiment will allow imaging of oceanic spreading center processes in the backarc, the formation and transport of island arc magmas, and the mineralogical phase transformations that accompany the subduction of oceanic lithosphere. In addition, an active arc-backarc system has many advantages from a passive imaging standpoint, since the features are essentially illuminated from below by an array of energetic, high frequency sources in subducting slab.

Geodynamic processes that can be imaged in an arc-backarc experiment include:

- *The structure of a backarc spreading center***.** The MELT and LABATTS experiments clearly showed widespread regions of low seismic velocity beneath spreading centers, but it is unclear what percent of partial melt is present, or how this pattern is related to mantle flow. A seismic experiment over a backarc spreading center has an advantage in that the seismic attenuation structure can also be determined, due to the presence of high energy nearby sources. The combination of velocity and attenuation structure places more constraints on the properties of the upper mantle, since they depend on temperature and melt content in different ways.

- *The source region of island arc magmatism***.** Island arc magmas are produced through the interaction of volatiles from the slab with hot material in the mantle wedge, but the exact process and its geometry are uncertain. There is considerable debate about which hydrous phases are involved, the depth of dehydration, the transport process and geometry between the slab and the near-surface, and what controls the position of the volcanoes relative to the slab. A passive imaging experiment could clarify the spatial extent and location of the melt production and transport zones in island arcs, a major focus of the MARGINS initiative.

- *The relationship of backarc and island arc magma source regions.* Backarc spreading centers generally show some geochemical signature of the slab, which can be accommodated by assuming input of a volatile component derived from the slab. Whether this interaction occurs directly at some distinct depth interval, or whether it simply involves fluxing of the entire mantle wedge has not been determined.

- *The mantle flow pattern in the backarc***.** Detailed mapping of seismic anisotropy provides an opportunity to relate seismic observations to large-scale mantle flow. The mantle flow pattern in island arcs is important for understanding both geochemical and geodyanmic processes in island arcs. Modeling of the strain resulting from flow coupled to the downgoing plate predicts a fairly uniform pattern of anisotropy paralleling the absolute plate motion. Geochemical constraints indicate a complex pattern of mantle source regions and thus mantle flow in the Tonga arc, qualitatively consistent with complicated shear wave splitting mapped by the LABATTS experiment (Figure 5). Numerical modeling of the induced lattice preferred orientation of olivine and orthopyroxene produces results that are non-unique and may only be fully tested with a more detailed mapping of the back-arc system.

- *Phase transformations and structure of subducting oceanic lithosphere.* Mineralogical reactions as the slab descends at a subduction zone include the dehydration of oceanic crust and sediments, and the basalt/gabbro to eclogite reaction. These reactions are fundamental to the formation of island arc magmas within the mantle wedge, yet the depths at which these transformations occur in the slab is uncertain due to questions about kinetics. Seismological constraints on the down-going crust have involved either phases that convert at the interface, or phases that travel along the strike of the slab as guided waves.

A major arc-backarc experiment would require a combined land-sea array of broadband seismographs. Land broadband stations offer the advantage of low cost and ease of installation, but good sites are limited in all arc-backarc settings. Therefore the major instrumentation necessary for an arc-backarc imaging experiment would be 40 to 75 broadband ocean bottom seismographs. The most logical places for a major experiment are in the Mariana or the Tonga island arc systems. Both island arcs have active backarc spreading centers with a mid-ocean ridge morphology. The Tonga system has more than 60% of the world's deep seismicity, thus providing a better source array, whereas the Mariana system has the advantage of being a selected study area of the MARGINS program.

An example of a currently possible arc-backarc experiment is shown in Figure 15. This experiment contains a 3-D array centered on the Tonga arc and Lau backarc spreading center, with a station spacing of 30 km. The 3-D array and smaller station spacing will allow superior resolution of the slab, island arc and back-arc spreading center structure.

Three-dimensionality of upwelling at a fast-spreading ridge (D. Toomey)

The pattern of mantle flow beneath fast spreading mid-ocean ridges and the magma plumbing system that transports melt from the upper mantle to the crust is still very poorly understood. Two fundamentally different models have been proposed. In one model there is a strong spreading-rate dependence to the pattern of mantle upwelling with focused, buoyantly-driven, diapiric flow beneath slow spreading ridges but more sheet-like, two-dimensional, plate-driven flow beneath fast spreading ridges (Figure 16a). An important implication of this model is that melt will be fed uniformly into crustal magma chambers at fast spreading ridges along the entire length of a ridge segment. An alternative hypothesis is that mantle upwelling is highly focused and diapiric at all spreading rates, but there is a more efficient along-axis distribution of melt in crustal magma chambers at fast spreading ridges, or ductile deformation of the hot, lower crust, which smoothes out any initial differences in crustal thickness (Figure 16c). This hypothesis is more consistent with localized, widely-spaced centers of magma injection into the crust as proposed for the East Pacific Rise (EPR) based on morphologic and petrologic evidence, and inferred from diapiric-like mantle flow structures mapped in ophiolites, especially in Oman. These are obviously two end member models. Melt may be supplied to the crust along the entire length of a segment but in greater volumes or more frequently at certain locations. The matrix flow of mantle material may be relatively 2-D, as predicted by simple corner flow models, but melt transport into the lower crust may be highly 3-D and variable along-axis (Figure 16b). The difficulty in differentiating between the end-member models is that they both predict relatively little variation in crustal thickness along-axis at fast spreading ridges. The controversy can be resolved only by imaging both crustal and mantle structures at a finer scale than previously attempted.

In addition to the debate over the relevance of passive or dynamic flow models to fast-spreading ridges, observations are accumulating that indicate that the EPR is not a simple, 2-D system. Active-source seismic studies reveal variations in crustal thickness of 1 to 2 km over distances of a few tens of kilometers both along

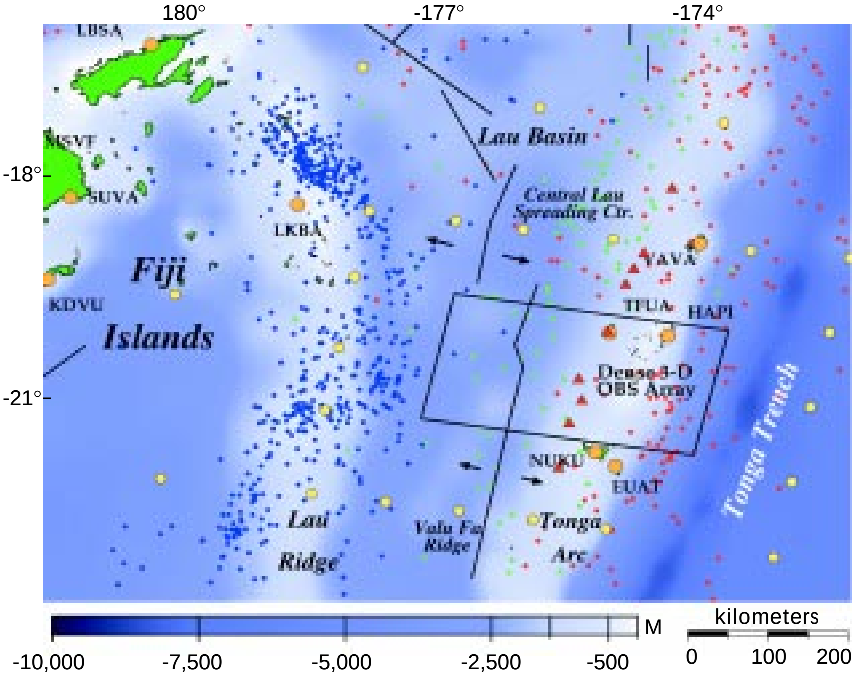

Figure 15. *Proposed experiment to image the Tonga volcanic arc and Lau backarc spreading center. A dense 3-D OBS array, with 30 km station spacing, is surrounded by a sparse array, for a total of 70-75 OBSs. Red dots indicate shallow earthquakes, green are intermediate earthquakes, and blue are deep earthquakes. Red triangles denote active volcanoes.*

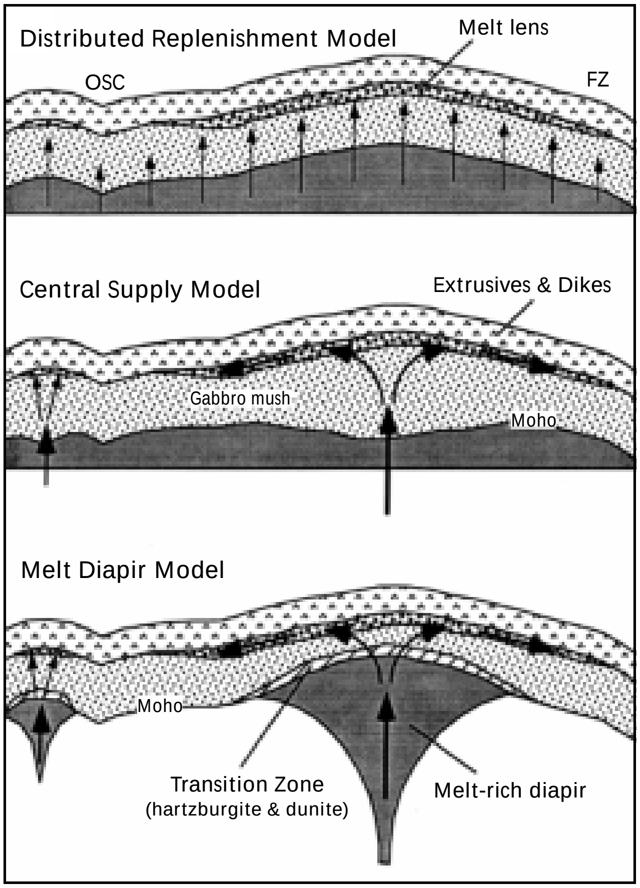

Figure 16. *Three models for formation of crust at fast-spreading ridges. (a) Top: Distributed supply model in which upwelling is shet-like(2-D). (b) Middle: Central supply model in which melt is supplied to center of segment by melt migration in the mantle, then redistributed along-axis by flow in axial magma chamber. (c) Bottom: Melt diapir model in which solid upwelling is concentrated in center and melt is redistributed along-axis either in shallow magma chamber or at base of the crust in crust/mantle transition zone (from of R. Dunn and D. Toomey).*

and across the rise axis. At the northern EPR, the Clipperton transform separates 100-km-long segments of the rise that show contrasting axial morphologies (broad vs. narrow cross-sectional area), contrasting axial crustal structure (clear AMC reflector vs. no AMC reflector), and contrasting mantle Bouguer anomalies. Yet seismic studies report a similar crustal thickness north and south of the transform, implying differences in mantle structure across the Clipperton. Investigating 3-D structure beneath a fast-spreading ridge and discriminating between the different types of flow models will require an experimental geometry different from that of the MELT experiment. The MELT experiment was designed to constrain primarily the cross-axis pattern of mantle flow and the geometry of the melt generation region and thus the array geometry for the MELT experiment consisted of linear arrays aligned sub-parallel to the spreading direction and separated by over 100 km (Figure 6). Even given the limitations of this array design for constraining along-axis variations in mantle structure, MELT investigators were able to demonstrate that mantle processes beneath the southern East Pacific Rise are distinctly three-dimensional.

Figure 17 shows a prototype of a seismic array design that could address the 3-D upwelling problem while also investigating tectonic features that offset the axial high. The design employs a nested array geometry in order to simultaneously provide broad spatial sampling throughout the array aperture and more detailed sampling through key geologic features. The broad aperture of the array will allow recovery of longer wavelength structure while 2-D sub-arrays will allow higher-resolution, 3-D imaging of individual targets (e.g., a regional axial high, an overlapping-spreading center, a near-axis seamount chain, or a ridge-transform intersection). Mapping differences in upper mantle structure across a large offset transform will require the larger array aperture. Surface wave data could be used to determine if, for example, large offset transforms demarcate boundaries to mantle structure as proposed for the Clipperton. Seismic anisotropy may be diagnostic of passive or diapiric upwelling. Passive flow models predict a simple 2-D seismic anisotropy, whereas diapiric upwellings should be associated with a 3-D, radial flow pattern and anisotropy signature, possibly superimposed on the broader passive flow. Detecting such signals will require relatively dense arrays in the vicinity of proposed diapiric upwellings. The magnitude of shallow mantle geophysical anomalies may also be diagnostic of 3-D flow. Evidence is accumulating from the MELT experiment that lateral variations in seismic velocities and electrical conductivity can be large over distances of kilometers to tens of kilometers. The detection of such signals bodes well for the future success of mantle dynamic experiments designed to investigate 3-D structure in the shallow mantle.

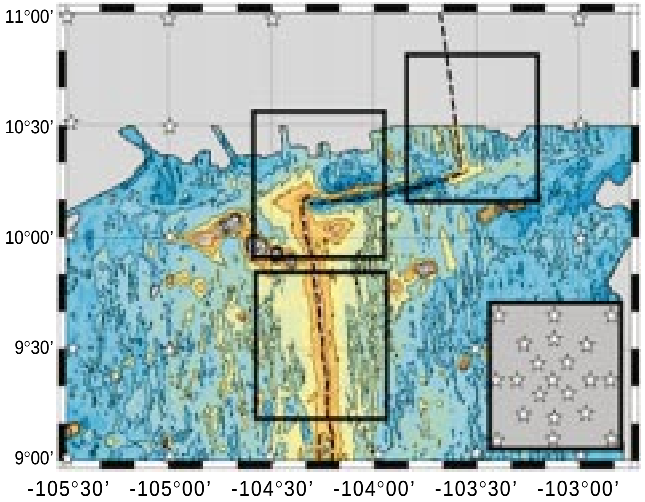

Figure 17. *Map of northern East Pacific Rise in the vicinity of the Clipperton Fracture Zone. Proposed OBS locations indicated by stars. The three boxes indicate the location of sub-arrays to provide more detailed resolution beneath plate boundaries, with possible design for sub-array shown in gray-shaded inset.*

Structure beneath a segmented, slow-spreading ridge (S. Webb and R. Detrick)

Over the past fifteen years a new model has emerged for crustal accretion at slow-spreading ridges, like the Mid-Atlantic Ridge (MAR). This model is based on the integration of results from detailed geophysical mapping of bathymetry and gravity over portions of the MAR, the distribution of lower crustal and upper mantle rocks recovered from the MAR rift valley and adjacent fracture zones, seismic refraction and microseismicity studies at the MAR ridge, and numerical and laboratory modeling of mantle flow and melt migration processes at ridge crests. In this model, crustal formation at the slow spreading MAR is viewed as a three-dimensional, temporally variable process driven primarily by the nature of mantle flow beneath the ridge axis and the variable thermal and mechanical properties of the lithosphere forming along a segment. The supply of melt to the crust is predicted to be focussed near segment centers. This results in the formation of a thick crust near segment centers and thinner crust near segment ends explaining the origin of the large, circular Bouguer anomaly (MBA) gravity lows or "bulls-eyes" observed along slow spreading ridges. Large, segment-scale variations in crustal thickness and axial thermal structure inferred from the existence of these gravity anomalies are also predicted to strongly affect both rift valley morphology and tectonics. At the middle of segments, thinner warm lithosphere and thicker crust leads to a narrow, shallower rift valley and small-offset, closely-spaced faulting. Thick, cold axial lithosphere and thin crust near segment ends allow a deep and wide rift valley to develop with large, widely-spaced faults some of which nucleate into long-lived, low-angle detachment faults which expose lower crustal and upper mantle rocks at the sea floor.

While this structural and tectonic model of the slow spreading Mid-Atlantic Ridge has gained wide acceptance over the past few years, the mechanism for focusing melt supply from the mantle near segment centers remains controversial. The most common explanation of this focusing is that it is associated with plume-like, buoyantly-driven mantle flow beneath segment centers, (Figure 18a), leading to increased melt production and a thickened crust beneath segment centers. Mantle diapirs beneath diverging plates have been simulated in the laboratory, in numerical models, and documented in the mantle section of some ophiolites lending further support to this interpretation. There is, however, no direct evidence for the existence of plume-like mantle flow beneath slow spreading ridges and serious questions have begun to emerge about this model. Although numerical modeling studies which include the buoyancy effects of partial melting have shown that convective instabilities could indeed develop in the mantle, the wavelength at which they form is typically 150-400 km, much longer than typical segment lengths of 50 km. The major element chemistry of basalts from portions of the Mid-Atlantic Ridge also fail to show the segment-scale systematics expected for greater extents and depths of melting near segment centers compared to segment ends as predicted by the mantle diapir model. The large increase in mantle viscosity due to dehydration at the onset of melting will further suppress the development of buoyant diapirs in the melting region.

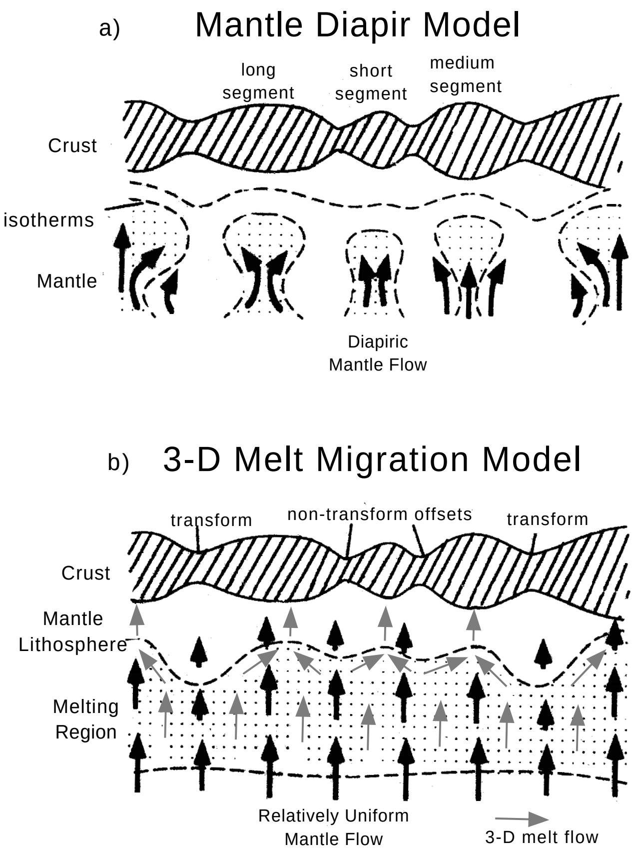

Figure 18. *a) model of upwelling associated with the formation of a series of diapirs due to convective instability in the upper mantle. Melt production and crustal thickness is controlled by the locations of the diapirs. b) model of passive upwelling controlled by the geometry of plate spreading (from* Magde et al.*, 1997).*

These observations have led to an alternative model (Figure 18b), in which upwelling even at slow spreading ridges is largely plate-driven and two-dimensional, but melt migration is highly three-dimensional and focused toward segment centers by variations in the thickness of the rigid lithosphere. In this model, lateral dike injection and/or lower crustal flow redistribute magma from the segment center toward the segment ends. Numerical modeling has shown this mechanism can readily produce the large variations in crustal thickness inferred from the MBA bulls-eyes. This kind of model is consistent with recent crustal seismic imaging at 35°N on the MAR which shows a <15 km diameter low velocity zone in the lower crust near the segment center which is continuous with a shallower, ~10 km wide, axis-parallel anomaly in the mid-upper crust, as well as with trace

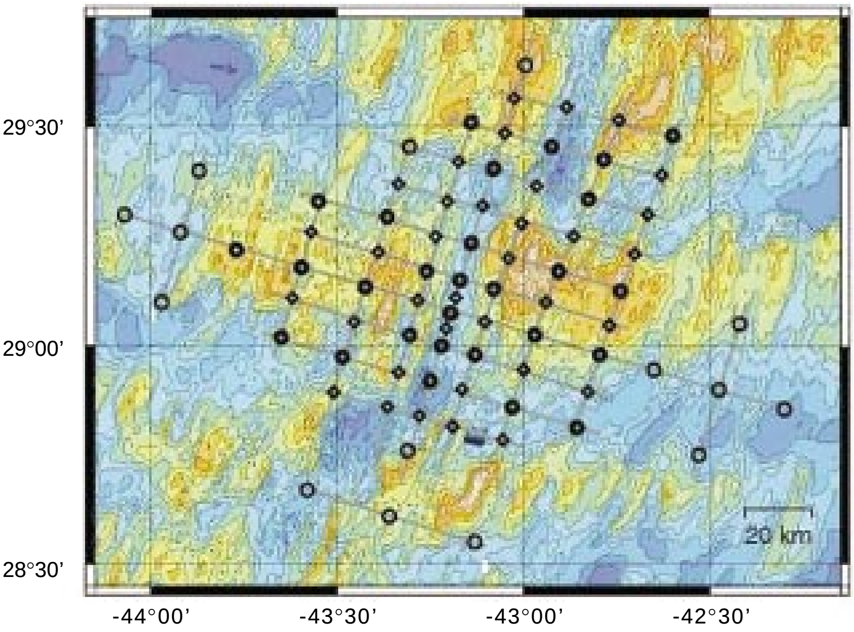

Figure 19. *Example of a combined passive/active array geometry for investigating 3-D crustal thickness variations and upper mantle structure beneath a segment of the slow spreading Mid-Atlantic Ridge near 29°N. Ocean bottom seismometers indicated by circles and hydrophones by diamonds. Airgun refraction shooting lines shown in gray.*

element geochemistry of ridge basalts which suggest that melt migration trajectories are very different from mantle flow paths. However, without more direct constraints on the pattern of mantle flow and distribution of melt at the segment-scale along a slow spreading ridge, the validity of either model shown in Figure 18 will remain uncertain.

These scientific questions can be addressed through a combined active source/passive teleseismic experiment to obtain a complete 3-D image of crustal and upper mantle structure at a segment of the slow spreading MAR (Figure 19). This kind of experiment would require a large array of ocean bottom seismometers (for the passive experiment) and ocean bottom hydrophones (for the active experiment). The seismic experiment must encompass an entire 60-80 km long ridge segment, as well as its adjacent offsets, and must extend a significant distance (~100 km) off-axis since crustal and upper mantle structure is expected to vary significantly both along-axis and across-axis. The active source experiment using a controlled airgun source and 80-100 OBS/H would provide the first 3-D tomographic image of variations in crustal velocity structure and thickness on the segment scale from the MAR. An OBS array of ~50 instruments deployed for about one year would record both local and teleseismic events. The teleseismic data could be used to study upper mantle structure beneath the ridge segment. Regional and teleseismic P and S body waves, surface waves and shear wave splitting studies would be combined to determine the presence of thermal and melt anomalies, and the pattern of flow-related anisotropy, in the upper 100 km of the mantle beneath the ridge. Through monitoring of local, segment-scale microseismicity over a 12-month period the relationship between strain release and lithospheric rheology, crustal thickness and mantle temperature variations could be determined. An electromagnetic (EM) experiment could be conducted in conjunction with this seismic study and would provide complementary constraints on the geometry of the melting region beneath the ridge, and the connectivity of the melt in the mantle.

Stratification of the oceanic lithosphere (J. Gaherty)

The processes of mantle flow, melting and crust formation at mid-ocean ridge spreading centers are fundamental to our understanding of the composition and dynamics of the Earth’s mantle. We have a sound understanding of many aspects of these processes, primarily due to extensive geologic and geophysical studies focused on oceanic crust. Basic questions remain, however, because we have very little knowledge of the structure of the complementary product of crust generation: the residual mantle. Crust extraction produces in the mantle a layer of residuum that is (1) depleted of basaltic constituents; (2) depleted of volatiles; and (3) embedded with structural fabric associated with melting and mantle flow beneath a spreading center. All three processes impart distinct seismic signatures, and this basic layered structure should remain in the lithosphere as it cools and translates from the ridge, providing a fingerprint of mid-ocean ridge processes over time.

The precise distribution of this seismic layering is diagnostic of several important aspects of melt-regime dynamics. For example, the presence, depth, and magnitude of seismic discontinuities associated with the transition in bulk composition should be diagnostic of the details of the melt-extraction process. Passive-upwelling models predict a smooth gradient in composition with depth, while buoyancy-driven-upwelling models predict an abrupt transition in composition with depth (Figure 20). Harzburgite has higher compressional-wave velocities (V_p) relative to lherzolite, so buoyant upwelling should result in an abrupt drop in V_p within the oceanic lithosphere. The depth and magnitude of the transition depend on the temperature of melting, degree of melt extraction, and the quantity of volatiles in the fertile mantle. Volatile content is particularly important, as volatiles are likely to strongly partition into the earliest melt fractions, enhancing the velocity contrast across the transition. Observations of seismic layering thus provide important constraints on several parameters associated with ridge dynamics that can be combined with geochemical observations and geodynamic models.

Measurements of seismic velocity with depth and azimuth can be used to distinguish between compositional and anisotropic transitions. The structural fabric of oceanic upper mantle rocks is a direct remnant of flow near the ridge axis, and numerical calculations suggest that lithospheric anisotropy is strongly dependent on the mechanisms of ridge-axis mantle flow (Figure 20). In these models, passive spreading generates a subhorizontal fabric in olivine that gradually increases in strength with depth through the lithosphere. In contrast, buoyant upwelling produces a lithosphere with relatively weak, subvertical fabric, underlain by a layer near 60 km depth characterized by very strong horizontal alignment. In terms of horizontal *P*-wave propagation, these models predict a strong (several %) gradational increase in apparent wavespeed for passive flow, and a large (up to 10%), abrupt increase in P velocity at 60 km for buoyant flow. In general, these depth variations are strongest in the direction of the plate flow line (perpendicular to the ridge axis), but they hold for the ridge parallel direction as well (~8% azimuthal variation).

Long-range seismic refraction lines provide the best opportunity to observe directly stratification of the oceanic lithosphere, and only a few such lines exist. Of these, several have found tantalizing evidence for layering. Studies from both the Pacific and Atlantic found abrupt velocity increases in the mantle between 25-60 km depth, and an additional experiment from the Philippine Sea found very high positive gradients in mantle velocity with depth. These velocity increases were interpreted in terms of compositional layering, but the velocity increase with depth is at odds with the negative velocity transition expected for simple harzburgite/lherzolite layering. The observations may be better explained by an increase in anisotropic fabric with depth, with abrupt increases indicating lithosphere formed at ridges with significant buoyant upwelling, and the gradational model indicating a passive spreading environment for the Philippine Sea plate. The lack of direct evidence for anisotropy associated with these profiles allows for alternative explanations, however, in particular compositional models invoking a deep eclogite layer. Additional evidence for mantle layering comes from passive-source studies of shallow reflectivity from a variety of isolated regions. These studies imply that the shallow oceanic

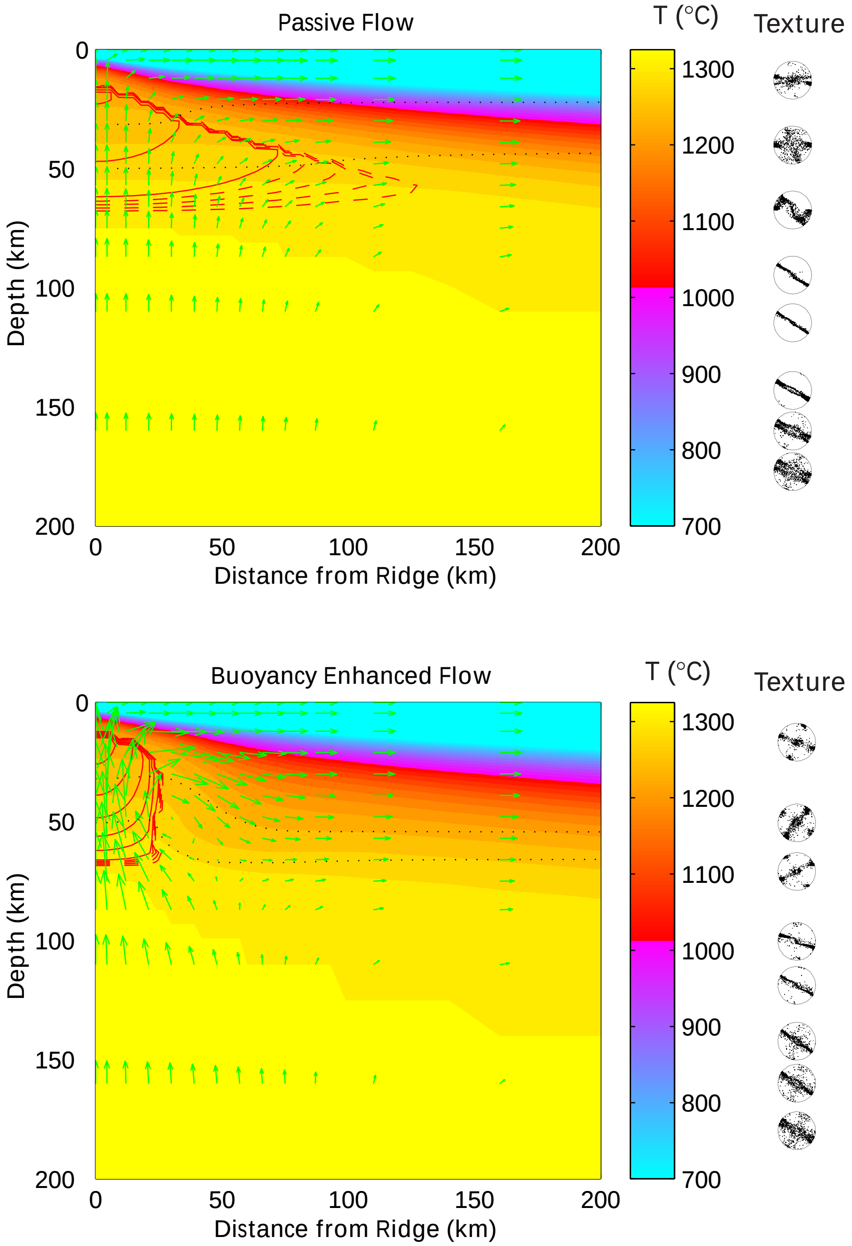

***Figure 20**. Finite element models of passive upwelling (top) and buoyant upwelling (bottom) at an oceanic spreading center. Mantle flow is passive when asthenosphere viscosity is 10^{20} Pa s; active when asthenosphere viscosity is 10^{18} Pa s. Upwelling mantle melts (red contours at 0.2% inteval below 1% (dash) and at 1% interval above this value). Melt in the interstices of the matrix contributes a buoyancy force. Mantle is depleted upon melting (black dotted contours at interval of 0.05, increasing upward) and this also contributes a buoyancy force. Also shown on the right are estimates of the orientation distributions of olivine a-axes, the direction along which P-waves propagate fastest. Each pole figure represents the mineral alignment that has developed in rocks that now reside more than 100 km from the spreading axis at the depth shown. (after Blackman et al., Geophys. J. Intl. 1996).*

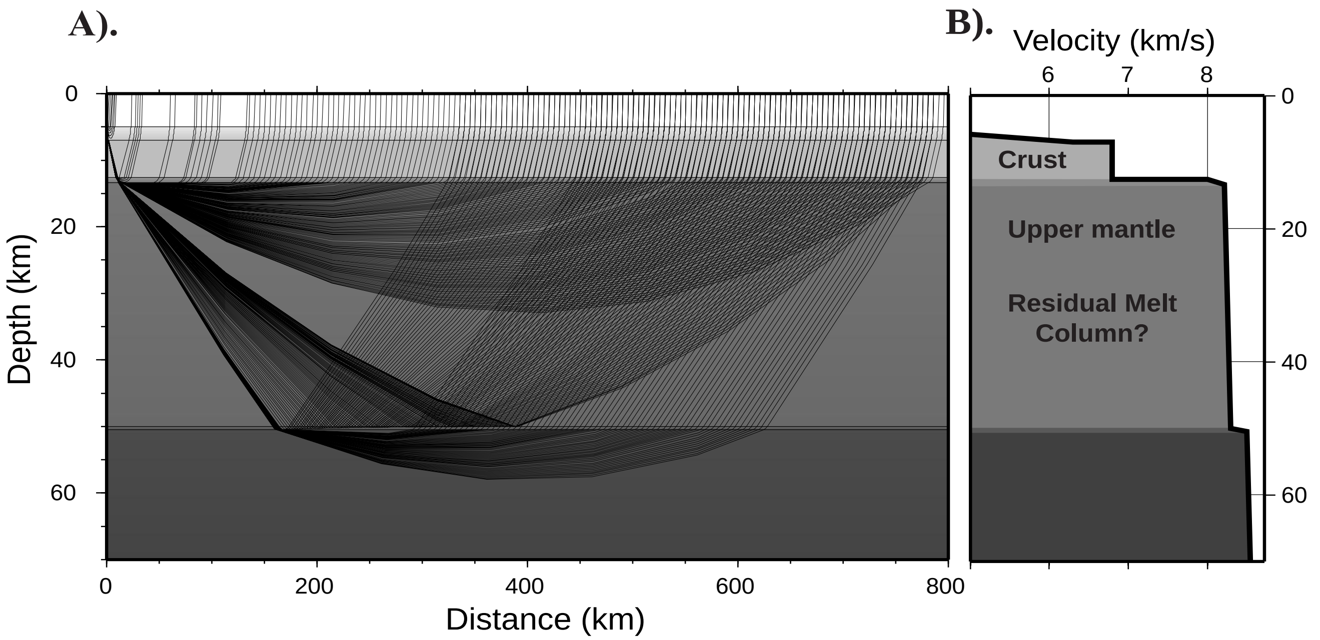

Figure 21. *A) Raypath coverage expected for a long-line refraction survey utilizing 14 OBS instruments, based on velocity model 2 (B) from LADLE [1983]. The upper 30 km of the mantle will have excellent ray coverage and should enable 2D tomographic inversion for structure within this depth interval. The triplication from a large veloicty gradient at ~50 km depth, perhaps the base of the residual melt column, is first observed at a range of 350 km, and the refraction from a high-velocity layer beneath this transition, perhaps a boundary of large anisotropy, becomes a first arrival at a range of 580 km.*

mantle is characterized by stratification in phase chemistry, volatile content, and/or anisotropic fabric, but that this stratification varies from region to region. Understanding details of the variation in layering would provide important new constraints on geodynamic processes.

The instruments in the OBSIP offers the means to construct focused experiments to illuminate the nature of seismic layering within the oceanic lithosphere and directly test the hypothesized origin of this layering. Such experiments would likely consist of both active- and passive-source components. An example active-source experiment is shown in Figure 21. This investigation involves the imaging of seismic layering beneath an 800-km line in the west-central Atlantic, using stacked airgun shots recorded at a set of 14 OBS instruments. Aligned along a plate-motion flowline, this study should provide relatively precise estimates of the depth, magnitude, and lateral continuity of both abrupt and gradational velocity changes within the upper 50-80 km of the lithosphere. Two off-line instruments provide the azimuthal coverage necessary to estimate the anisotropic contribution to the layering.

The incorporation of a passive-source component can enhance the lateral extent and sampling depth of this experiment. A 6-12 month deployment of 3-component OBS instruments would provide sufficient data from large earthquakes for a detailed *Ps*-conversion (“receiver function”) study of the layering beneath the stations. Such an analysis provided excellent resolution of the depth and relative magnitudes of the 410-km and 660-km discontinuities in the MELT experiment, and illuminated previously unknown (and yet to be explained) reflectors near 200-km and 600-km depth. Application of this technique to shallower mantle discontinuities is straightforward. A passive-source deployment also provides a suite of information on the structure of the lithosphere and upper mantle that will assist in constraining the mechanisms responsible for layering. These include estimates of lithosphere velocities from surface-wave velocities and local/regional delay times, and estimates of anisotropy from surface waves and shear-wave splitting.

The deployment of such experiments in two or three regions with contrasting spreading styles (for example, lithosphere formed at the slow-spreading MAR and the fast-spreading EPR) would provide baseline measures of upper mantle structure for “normal” oceanic lithosphere and an interpretation of that structure in terms of normal ridge processes. Because this baseline stratification is likely to be perturbed by major thermal, volcanic, and other tectonic events, studies of lithospheric layering provide an additional means to address many outstanding problems related to mantle dynamics in the marine environment. Possible targets include layering (and the perturbation thereof) associated with hotspots and plumes; large igneous provinces; plume-ridge interactions; along-ridge thermal variation; temporal variation of spreading and crust extraction; back-arc basins; and so on.

Depth Distribution of Anisotropic Fabric in the Oceanic Mantle (K. Fischer)

There has long been a debate over how much of the anisotropic fabric recorded in shear wave splitting is fossil fabric frozen into the lithosphere from an earlier tectonic event and how much is generated by current deformation in the asthenosphere. Unraveling these competing signatures is critical for understanding the pattern of flow in the mantle. Shear wave splitting is best measured on near vertical paths using phases such as SKS that traverse through the entire upper mantle, yielding essentially no depth resolution of anisotropy. Even when splitting tomography is possible through comparison of splitting on non-vertical paths crossing paths to closely spaced stations, in a laterally uniform medium, there is no depth resolution of anisotropy. All that can potentially be resolved in such a tomographic study is the lateral variation in anisotropy, not the absolute values at any given depth. When there are two layers with anisotropy of different orientation, then the relative amounts of splitting in the two layers theoretically can be resolved by measuring the degree of splitting from sources with a wide range of azimuthal polarizations, although the thicknesses and depths of the layers cannot be uniquely resolved. This approach has been successful in a few studies, although the distribution of sources often is less than ideal.

Another approach that can provide vertical resolution is to measure the azimuthal anisotropy of Rayleigh surface waves. These waves sample a limited, frequency-dependent depth range in the upper mantle and are sensitive to the same anisotropic parameters as vertically travelling S waves. In young seafloor in the Pacific where the absolute plate motion and fossil, relative plate motions are similar, azimuthal anisotropy is strong. In the western Pacific, azimuthal anisotropy seems to be much weaker. This weakening may be caused by the interference between fossil anisotropy and anisotropy generated by asthenospheric flow in an area where fossil and absolute plate motions differ.

An ideal location to unambiguously resolve the depth of origin of anisotropy in the oceanic mantle is in the vicinity of one of the "magnetic bights" left behind by sea floor created on two of the branches of a ridge-ridge-ridge triple junction (Figure 22). In a relatively small area, there are major changes in the direction of fossil seafloor spreading in seafloor of the same age and similar spreading rate. Thus, the fossil component should change direction dramatically, but the asthenospheric component should be nearly constant. With an array or arrays covering both arms of the bight as well as the region of change, all three methods of addressing the depth of the anisotropic layers and the relative distribution between lithosphere and asthenosphere could be employed. SKS phases from teleseismic sources and ScS waves from deep focus earthquakes in the Mariana, Izu-Bonin, Japan and Kurile subduction zones could be used for tomographic imaging in the region of change and for resolving the relative amount of splitting on each of the two arms of the bight. Surface waves propagating across the arrays from shallow earthquakes distributed

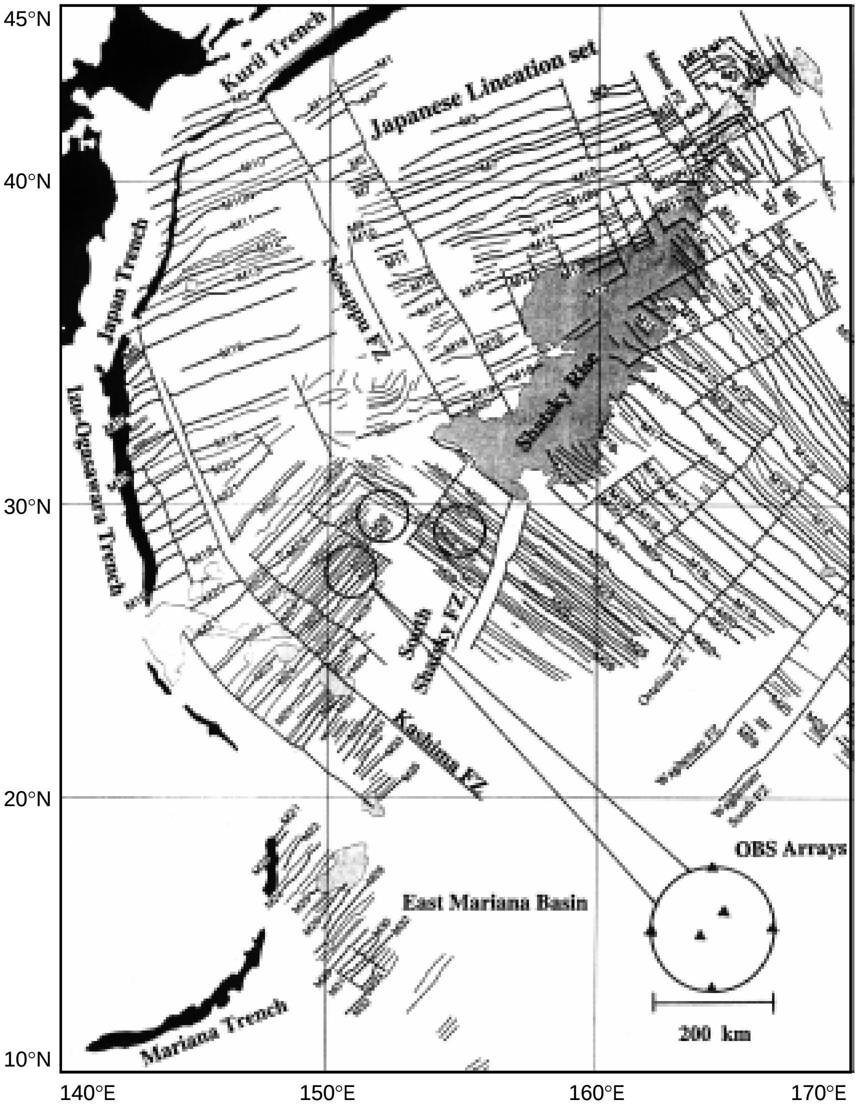

Figure 22. *Example of an experiment designed to detect relative roles of oceanic lithosphere and asthenosphere in generating shear-wave splitting. Passive OBS arrays would detect changes in shear-wave splitting and azimuthal anisotropy of surface waves associated with change in direction of fossil sea-floor spreading as indicated by these Mesozoic magnetic anomalies in the western Pacific (*Nakanishi, et al.*,1992).*

around the globe should provide good resolution of azimuthal anisotropy as a function of period with equal quality in each region. In a one-year deployment, enough events should be recorded to clearly resolve the thickness and depth of the anisotropic lithosphere and asthenosphere as well as the direction of shear in the asthenosphere.

Deep structure of ocean-continent transitions (D. Forsyth)

Numerous geodynamic models of the formation of rifted continental margins have been developed over the past two decades. These models include both simple, conceptual representations such as uniform stretching of the lithosphere in pure shear or rifting along major detachment zones in simple shear, and more complex numerical models with variable rheology. One driving motivation behind the development of many of these models is the need to understand the formation, thermal history, and subsidence of sedimentary basins. The amount of initial tectonic uplift or subsidence and the amount of subsequent thermal subsidence is largely controlled by the relative amount of stretching of the crustal and mantle components of the lithosphere. Although the mantle thus plays a fundamental role in the development of sedimentary basins and there has been an enormous effort invested in imaging the sediment column and to some extent the underlying crust, very little is known about the nature of the ocean-continent transition at mantle depths.

Existing images of the ocean-continent transition that include the mantle come primarily from regional or global studies of upper mantle structure. In the stable cratons, the high-velocity, seismic lithosphere is thicker than in oceanic regions, and the low-velocity zone may be entirely absent. Along the Atlantic continental margin, the transition from oceanic-style asthenosphere to continental root seems to occur well inland of the continental slope (Figure 23), presumably representing some remnant of the rifting process. The lateral resolution is poor, however, so it is not known exactly where the transition is, what controls its location, or whether there is a second transition in structure near the actual ocean-to-continental crust boundary representing the transition from stretching to spreading.

One experimental approach to improving resolution of the transition would be to mount a combined onshore/offshore campaign in conjunction with the USArray deployment of land stations. This campaign could include both active and passive seismic experiments, but should include an array of OBSs deployed with density and duration comparable to the USArray deployment in the area of interest. Receiver function studies could then provide information about crustal and mantle discontinuities beneath the stations, body and surface wave tomography could be employed to image mantle structure to depths of several hundred kilometers, and shear wave splitting analyses would reveal whether any change in anisotropy is associated with the onset of seafloor spreading. Lateral resolution would be an order of magnitude better than in any existing study.

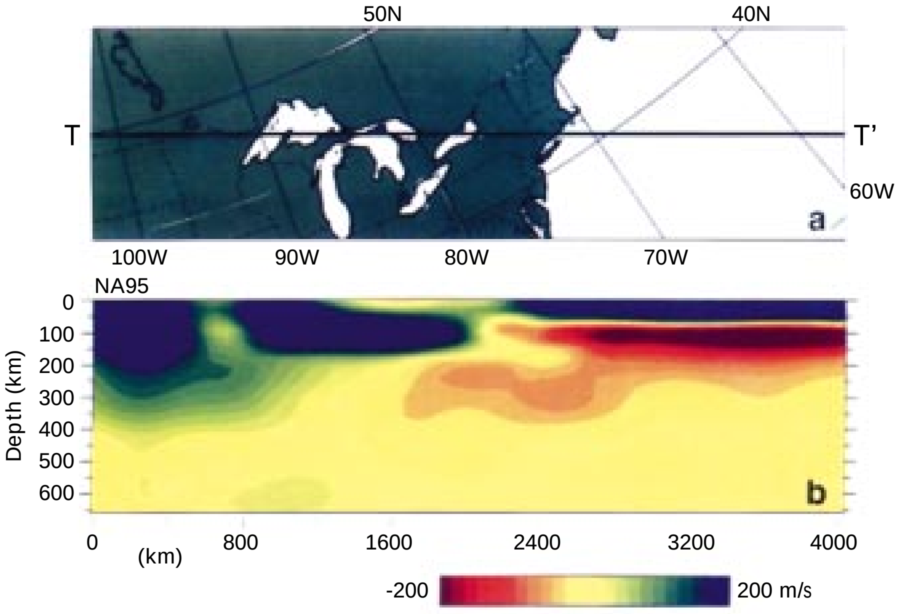

Figure 23. *Cross-section showing shear velocity anomalies across the continent-ocean boundary of eastern North America (from* van der Lee and Nolet, *1997). Note extension of oceanic asthenosphere (red shades) into sub-continental mantle (location of section shown by T-T' in a). Lateral resolution is on the order of 500 km.*

6.0 Filling Gaps In Global Seismic Station Coverage —Leapfrogging Regional Arrays

Large gaps exist in the coverage of the Global Seismic Network (GSN) over the 70% of the Earth's surface covered by water that cannot be filled with island stations. These gaps in coverage, especially in the Southern Oceans and parts of the eastern Pacific, Atlantic and Indian Oceans:

- limit the resolution of inner core anisotropy;

- prevent mapping of much of the core-mantle boundary and lowermost mantle – a region that is probably the origin for hotspots and may be the resting place for dead slabs;

- introduce bias into spectral studies of mantle heterogeneity;

- cause aliasing between lateral heterogeneities and azimuthal anisotropy in the upper mantle;

- limit resolution of regional upper mantle structure; and,

- in some areas, increase the detection threshold for earthquakes and explosions

In order to address this problem, a permanent Ocean Seismic Network (OSN) consisting of ~20 high-quality, broadband (0.0003-5 Hz), permanent stations on the seafloor has been proposed as part of the International Ocean Network (ION) (see Appendix 2). The locations of proposed ION/OSN sites as recommended by *Purdy and Dziewonski* (1988) and *Montagner and Lancelot* (1995) are shown in Figure 24. Sites are located in the Indian, Atlantic and Pacific Oceans in areas lacking nearby island or continental sites.

Significant progress has been made in the past few years in addressing the technical problems associated with the deployment and recording of observatory-quality seismic stations on the seafloor. The 1998 OSN Pilot Experiment, carried out by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution at the OSN-1 drill site (ODP Hole 843B) 225 km southwest of Oahu, demonstrated the technical feasibility of deploying seafloor and buried broadband seismometers (BBOBS) and a borehole broadband instrument using wireline reentry and ROV technology. This pilot experiment also showed that that seafloor broadband seismic stations with performance comparable or superior to nearby island stations are now feasible

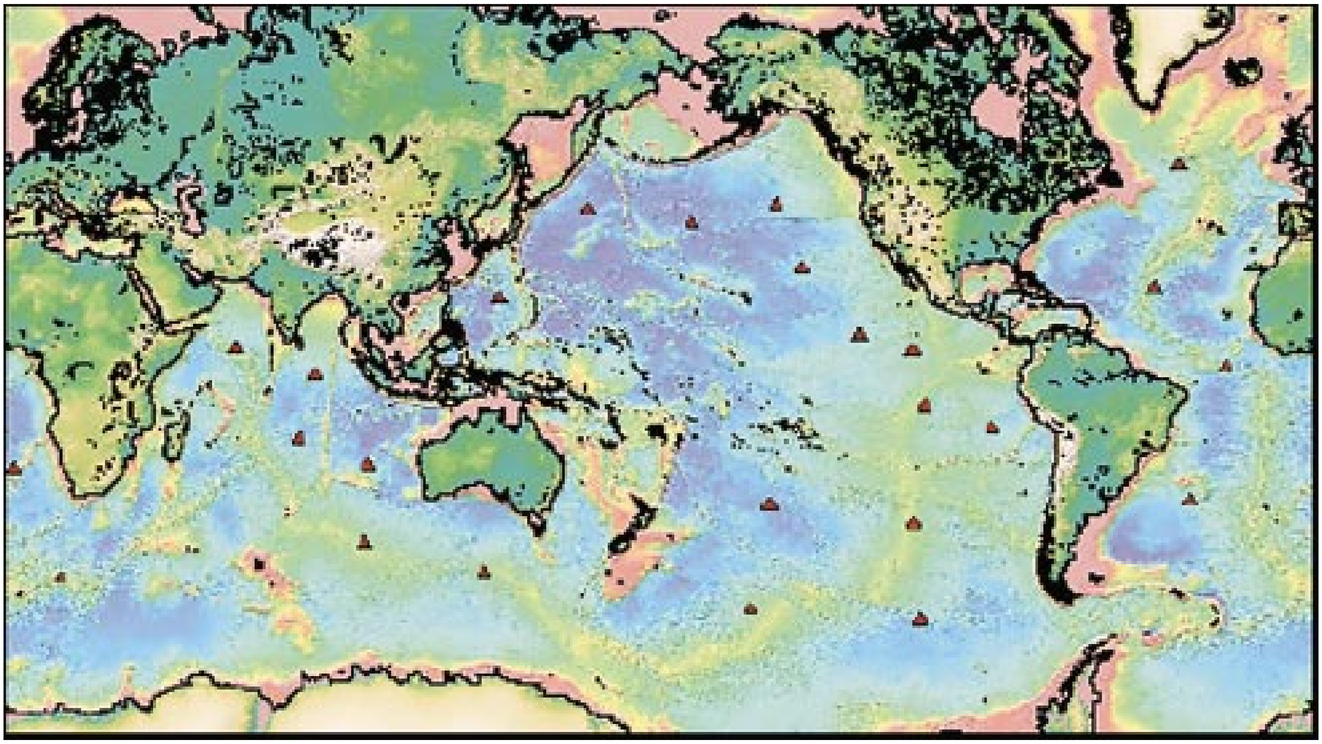

Figure 24. *Locations of prospective ION/OSN sites as recommended by* Purdy and Dziewonski *(1988) and* Montagner and Lancelot *(1995).*

(Collins et al., in press). Permanent stations will ideally be located in shallow boreholes to reduce noise levels near and above the microseism peak, although if a borehole is not available high-quality data can be obtained, especially below 0.1Hz, with a sensor buried at shallow depths in sediment.

The first broadband seismic station on the deep seafloor using modern technology was established in 1998 at the H20 site in the North Pacific between Hawaii and North America. Here a buried broadband sensor was installed and data are being telemetered in real time to shore using an abandoned telecommunications cable. In collaboration with the international Ocean Drilling Program (ODP), significant progress has also been made in preparing several of the OSN sites for permanent seismic installations. A shallow hole has been drilled at the NERO site in the Indian Ocean, a hole is scheduled to be drilled at the H20 site in 2001, and proposals have been submitted for OSN holes in the Equatorial Pacific and on the Nazca plate. Real-time data telemetry from NERO, equatorial Pacific and Nazca Plate seismic observatories will require a moored buoy system like that under design as part of the DEOS (Dynamics of Earth Ocean Systems) ocean observatory planning effort.

While progress is being made in establishing a permanent OSN, it will be many years before the full network of stations is in place. Although not a replacement for high-quality, long-term seafloor seismic stations that are needed for recording rare events such as major earthquakes and earthquakes in usually quiescent spots, leapfrogging regional seismic arrays can help fill in the major gaps in global seismic coverage shown in Figure 21. These arrays would provide a density of coverage not possible for more expensive, long-term stations, allowing better imaging of regional upper mantle structure in the gap areas. In addition, the measurements of changes in waveform and relative arrival time across the array would complement the information provided by the long-term stations. If the leapfrogging array preceded the installation of a long-term station, the measurements of noise could help select a quiet site.

With on the order of 10 stations in each array, there would be redundancy that would virtually guarantee good data coverage for the duration of each deployment. Each deployment would be designed individually to optimize the coverage for a particular tectonic problem unique to that region, in addition to filling a gap in global coverage. Each array would be deployed for about one year to ensure adequate sampling of earthquakes with a global distribution for global structural studies. Part or all of the first OMD workshop could be devoted to designing the leapfrog sequence, establishing basic principles of design of each array, and devising a process for selecting investigators to design and manage each deployment.

7.0 Scope And Costs

In a decade of focused experiments, tremendous progress could be made towards solving the outstanding geodynamic questions about the form of flow in the oceanic upper mantle. At least one example of all the major types of oceanic tectonic settings recognized today could be investigated and global resolution could be improved as well by adding these seismological data sets to those provided by permanent or very-long-deployment stations. The following would be the major components of an Oceanic Mantle Dynamics (OMD) initiative:

- **One to two major field projects/year**

  Number of experiments depends on number of instruments needed for each and duration of deployment required.

- **~10 shore-based ancilliary investigations/year**

  Including laboratory experiments and analysis, geodynamical modelling, and analysis of existing data sets or data sets from prior experiments

- **Two leapfrogging regional arrays in continuous operation to help fill in gaps in global seismological coverage**

  Each regional array or pair of arrays has a PI responsible for designing and supervising that year's deployment and ensuring prompt transfer of quality-controlled data to IRIS Data management center. (Appendix 3)

- **One workshop each year**

  Each workshop will focus on different aspects of oceanic mantle dynamics, but including progress reports on interpretation of experiments

Costs: We estimate the cost of a program with the components outlined above to be about $6.1M/yr plus shiptime. The following is a breakdown of these costs:

Major field programs: We assume a typical major field experiment will involve a 3-to-4 yr grant for ~$1.5M for science costs + ~$0.8M for OBS deployment costs + ship costs. The $1.5M 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/year to carry out OBS deployment/recoveries and ancillary sampling and surveying, for a total of 4 legs/yr.

Leapfrogging arrays: A leapfrogging array proposal is assumed to be a 2-year, $150K grant for each year's PI + $200K in OBS deployment costs + ship costs. The OBS costs are estimated assuming 10 instruments with a buried intermediate-band sensor at $20K/instrument. Two legs will be required each year for OBS deployment/recoveries.

Shorebased projects: typically a 2 yr grant for ~$180K total

Workshop and management: $150K/yr

Total costs/year in today's dollars assuming 3 major field programs every 2 years, 2 leapfrog array deployments each year, and 10 ancillary shore-based studies will be: 1.5 x (1.5M + 0.8M) + 2 x (0.15M + 0.2M) + 10 x (.18M) + .15M = $6.1M/yr

8.0 Management

Management of the OMD initiative will be based on the following principles:

- Management costs will be kept as low as possible to provide as much science for the dollar as possible.

- Projects will be selected by competitive peer review through the normal NSF Ocean Sciences structure.

- Projects eligible for funding from the OMD Initiative will have to be certified as relevant by the steering committee.

- Seismological data sets will be supplied to the IRIS Data Management Center (Appendix 3) within one year after the recovery of the instruments. They will be available for general public use immediately in the case of the leapfrogging experiments and within two years after recovery in the case of the major field projects.

- Steering committee will comprise six members, two each from the seismology, petrology/geochemistry, and geodynamics/geophysics communities, plus a chair.

- Steering committee is responsible for relevancy review of proposals, selection of an annual workshop topic, appointment and recruitment of a workshop committee, selection of annual PI for the leapfrogging array, selecting the next chair and new members, and any other organizational decisions to be made.

- 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, monitoring prompt delivery of data sets to data management center, and acting as spokesperson for the initiative when necessary.

- The chair of the 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.

USGS/Hawaii Volcano Observatory

References

Blackman, D.K., J.-M. Kendall, P.R. Dawson, H.-R. Wenk, D. Boyce, J. Phipps Morgan, Teleseismic imaging of subaxial flow at mid-ocean ridges: travel-time effects of anisotropic mineral textrue in the mantle, *Geophys. J. Intl.*, 127, 415-426, 1996.

Braun, M.G., G. Hirth and E.M. Parmentier, The effects of deep damp melting on mantle flow and melt generation beneath mid-ocean ridge, *Earth Planet. Sci. Lett.*, 176, 339-356, 2000.

Collins, J., F.L. Vernon, J.A. Orcutt, R.A. Stephen, K.R. Peal, F.B. Wooding, F.N. Spiess and J.A. Hildemand, Broadband Seismology in the Oceans: Lessons from the Ocean Seismic Network Pilot Experiment, *Geophys. Res. Let.*, in press, 2000.

LADLE Study Group. A lithospheric seismic refraction profile in the western North Atlantic Ocean, *Geophys. J. R. Astr. Soc.*, 75, 23-69, 1983

Langmuir, C.H., E.M. Klein, and T. Plank, Petrological systematics of mid-ocean ridge basalts: Constraints on melt generation beneath ocean ridges, in *Mantle Flow and Melt Generation at Mid-Ocean Ridges, Geophys.* Monogr. Ser., vol. 71, ed. Phipps Morgan, Blackman and Sinto, AGU, pp. 183-280, Washington, D.C., 1992.

Laske, G., Phipps Morgan, J., and J.A. Orcutt, First results from the Hawaiian SWELL pilot, *Geophys. Res. Let.*, 26, 3397-3400, 1999.

Magde, L.S. , D.W. Sparks and R.S. Detrick, The relationship between mantle flow, melt migration and gravity bull's eyes at the Mid-Atlantic Ridge between 33°N and 35°N, *Earth Planet. Sci. Lett.*, 148, 59-67, 1997.

MELT Seismic Team, Imaging the deep seismic structure beneath a mid-ocean ridge: The MELT experiment, *Science*, 280, 1215-1218, 1998.

Montagner J.-P., and Y. Lancelot, Multidisciplinary observatories on the deep seafloor, International Workshop Report, 229 pp., 1995.

Nakanishi, M., K. Tamaki, and K. Kobayashi, Magnetic anomaly lineations from Late Jurassic to Early Cretaceous in the west-central Pacific Ocean, *Geophys. J. Int.*, 109, 701-719, 1992.

Purdy, G.M. and A.M. Dziewonski, Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean, Woods Hole Ocean. Inst. 331 pp., 1988.

Sandwell, D.T., E.L. Winterrer, J. Mammerickx, R.A. Duncan, M.A. Lynch, D. Levitt, and C.L. Johnson, Evidence for diffuse extension of the Pacific plate from Pukapuka ridges and cross-grain lineations, *J. Geophys. Res.*, *100*, 15087-15099, 1995.

Smith, W.H.F., and D.T. Sandwell, global seafloor topography from satellite altimetry and ship depth soundings, *Science*, 277, 1956-1962, 1997.

Toomey, D.R., J.A. Conder, W.S.D. Wilcock, D.W. Forsyth, J. Blundy, E.M. Parmentier, Asymmetric mantle dynamics in the MELT region of the East Pacific Rise, *Nature*, submitted, 2000.

van der Lee, S. and G. Nolet, Upper mantle S velocity structure of North America, *J. Geophys. Res.*, 102, 22815-22838, 1997.

Wolfe, C.J., and S.C. Solomon, Shear-wave splitting and implications for mantle flow beneath the MELT region of the East Pacific Rise, *Science*, 280, 1230-1232, 1998.

Zhao, D., D. A. Wiens, L. Dorman, J. Hildebrand, and S. Webb, High resolution tomography of the Tonga subduction zone and Lau backarc basin, *Science*, 278, 254-257, 1997.

Appendices

Appendix 1
US National OBS Instrumentation Pool (OBSIP)

The NSF's Ocean Science Division has recently established a National Ocean Bottom Seismic Instrumentation Pool (OBSIP) to make a new generation of ocean bottom seismic instrumentation available to the broader geosciences community. There will be three institutional contributors to the instrument Pool: the Scripps Institution of Oceanography, the Woods Hole Oceanographic Institution, and the Lamont-Doherty Earth Observatory. The instruments in the Pool will be available for use by any interested U.S. investigator.

The instrument Pool will initially consist of two types of instruments, ~135 compact, inexpensive 2-component OBH/S instruments for short-deployment, active source crustal seismic experiments and rapid response studies, and >100 long-deployment (up to 12-15 months) four-component OBS equipped with a hydrophone and a 3-component seismometer with excellent short and intermediate period response for regional earthquake and teleseismic investigations. Technical specifications for the instruments being constructed for the Pool are available on the OBSIP web site at www.obsip.org. The full suite of active source instruments will be available for use by late 2001; the 100+ long-deployment instruments are expected to be in service by the end of 2002.

The OBSIP will provide information to potential users on the availability of Pool instruments, and will work with users to match their scientific needs with available instrumentation. The three institutional instrument contributors will provide complete operational and technical support for OBS operations at sea. The cost of OBS operations (e.g., shipping, instrument charges, and technical support) will be funded through the Pool. PIs will, however, be required to include an informational budget in their proposal outlining these costs. Data will be provided to users in a standard PASSCAL SEGY format. All data collected with Pool instruments will be archived in a central data repository, and will be available to any interested investigator after a proprietary period consistent with NSF policy.

OBSIP will begin supporting field programs in 2001; the Pool will be fully operational by the end of 2002. For additional information on OBSIP or requesting OBSIP instruments see the OBSIP web site at: www.obsip.org.

Appendix 2
Ocean Seismic Network

The establishment of ~20 high quality, broadband (0.003-5 Hz), permanent Ocean Seismic Network (OSN) stations on the seafloor are envisioned as part of the International Ocean Network (ION). The locations of proposed ION/OSN sites as recommended by Purdy and Dziewonski (1988) and Montagner and Lancelot (1995) are shown in Figure 21. Sites are located in the Indian, Atlantic and Pacific Oceans in areas lacking nearby island or continental sites.

Significant progress has been made in the past few years in addressing the technical problems associated with the deployment and recording of observatory-quality seismic stations on the seafloor. The 1998 OSN Pilot Experiment, carried out by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution at the OSN-1 drill site (ODP Hole 843B) 225km southwest of Oahu, demonstrated the technical feasibility of deploying seafloor and buried broadband seismometers (BBOBS) and a borehole broadband instrument using wireline reentry and ROV technology (Collins et al., in press).

All three of the broadband instruments recorded data continuously and autonomously on the seafloor from the time they were deployed in early February until late May or early June (at least 115 days). Over fifty teleseismic earthquakes were observed on the broadband systems ranging from a 4.5Mb event at 44° epicentral distance (2/14/98 2:15:03) to the 8.0Mw Balleny Islands earthquake at 91° epicentral distance (3/25/98 3:12:26). Signal to noise ratios for earthquakes varied depending on frequency band, ambient noise conditions, and sensor design. Analysis indicates that the borehole broadband seismic installation provided comparable- to superior-quality data in comparison with similar continental and island stations over the band from 0.003 to 5Hz and that the shallow buried broadband system compared very favorably with the borehole system for signals in the frequency band from 0.01 to 0.07Hz (Collins et al., in press). However, within the microseism band (0.1-5 Hz), the background noise levels recorded by the borehole seismograph are substantially less than the levels on the buried BBOBS, while (surprisingly) at frequencies below 10 mHz, the noise level of the borehole instrument rises and the buried BBOBS is the quietest instrument. Within the microseism band, the background noise levels of the seafloor and buried BBOBS are similar. However, at frequencies less than ~0.1 Hz, the seafloor BBOBS is 20-40 dB noisier than the buried BBOBS. At these frequencies the detection threshold of events on a seafloor BBOBS will be substantially higher than for a seafloor BBOBS with a buried sensor. The high background noise levels of the seafloor BBOBS appear to be due to ocean-bottom currents pushing on the seismometer and the seafloor, generating tilt-induced accelerations.

The OSN Pilot Experiment demonstrated that seafloor broadband seismic stations with performance comparable or superior to nearby island stations are now feasible. The permanent stations will ideally be located in shallow boreholes to reduce noise levels near and above the microseism peak, although if a borehole is not available high-quality data can be obtained, especially below 0.1Hz, with a sensor buried at shallow depths in sediment. This is the primary motivation for the leapfrog array proposed as part of the OMD initiative.

The first operating broadband seismic station on the seafloor was established in 1998 at the H20 site in the North Pacific between Hawaii and North America. Here a buried broadband sensor was installed and data are telemetered in real time to shore using an abandoned telecommunications cable. In collaboration with the international Ocean Drilling program, significant progress has been made in preparing several of the OSN sites for permanent seismic installations. A shallow hole has been drilled at the NERO site in the Indian Ocean, a hole is scheduled to be drilled at the H20 site in 2001, and proposals have been submitted for OSN holes in the Equatorial Pacific and on the Nazca plate. Real-time data telemetry from NERO, equatorial Pacific and Nazca Plate seismic observatories will require a moored buoy system like that which is being developed as part of the DEOS initiative.

Appendix 3

IRIS/PASSCAL Data Management Center

The IRIS Data Management Center (DMC) is located in Seattle, Washington, just off the University of Washington campus where the Geophysics Program acts as the host organization. The IRIS DMC receives earthquake and seismic data from a variety of Data Collection Centers and is responsible for the long term archive and distribution of all IRIS generated data, including data from regional, limited-term deployments such as envisioned in several of the above descriptions of possible experiments. The DMC is just one part of the IRIS Data Management System.

The IRIS DMS presently consists of six components or “nodes”. These nodes work together to insure the smooth flow of GSN data from the stations to the seismological research community.

Data Management Center (DMC) in Seattle, Washington. The archive and distribution center for the two instrument components of IRIS (GSN and PASSCAL) as well as data from a variety of other networks.

IRIS/IDA Data Collection Center in La Jolla, California. Operated by personnel from the Scripps Institution of Oceanography, part of the University of California at San Diego.

The Moscow Data Center (MDC) in Moscow, Russia. The MDC receives support from the IRIS DMS for a variety of activities including enhancements to PITSA (an interactive tool for seismological analysis) and development of a program to convert hypocenter information formats into the WMO New Telegraphic Standard.

IRIS/USGS Data Collection Center in Albuquerque, New Mexico. Operated by the United States Geological Survey at the Albuquerque Seismological Laboratory.

University of Washington in Seattle, Washington. The host of the IRIS DMC routinely reviews data from earthquakes at the DMC and is responsible for the development and maintenance of the system that recovers data from significant earthquakes in near real time from stations all over the world.

Waveform Quality Center (WQC) at Harvard University in Cambridge, MA. The WQC uses IRIS GSN data in its routine calculation of the Centroid Moment Tensor Solutions for earthquakes and reports data quality problems to the DMS.

Eruption of Pu'u O'o volcano, Hawaii. *(Photo courtesy of USGS/Hawaii Volcano Observatory)*