

Deep Submersibles and Potential Marine Geological, Biological, and Geochemical Research

Scientific justification for the need for a greater depth-capability in occupied submersibles

Introduction

This document is based on an article published in the Marine Technology Society Journal (Fryer, 1990) with updates from Fryer, the DEep Submergence Science Committee of UNOLS, and several members of the research community (notably, L. Levin, M. Kastner, C. van Dover, M. Rex, R. George, R. Lucas, and D. Luthor).

Science Background

Many of the most significant discoveries made during the past two decades of marine research have been the direct result of the relatively few submersible dives made in each of the three types of areas on which marine geologic research is focused. Dive results provided us with the first detailed looks at the structure and the nature of volcanism along a mid-ocean spreading ridge (e.g. Ballard and Van Andel, 1977), and with the first comprehensive maps of the variation in composition of lavas within a ridge crest (e.g. Bryan and Moore, 1977). The detailed understanding of hydrothermal venting at ridge crests and the proliferation of organisms associated with those vents might never have developed without the submersible work done at these sites over the past 3 decades. The study of deep exposures in fracture zone walls separating segments of actively spreading ridge crests was facilitated by submersible work (Schreiber and Fox, 1977; Mevel et al., 1991). The nature of the activity on mid-oceanic volcanoes could not have been documented without the observations and sampling done with submersibles (e. g. Craig et al., 1987a). Studies of the deep ocean basins are precluded from study by submersibles with depth capability of less than 4500 m. Until a deep US submersible dedicated to marine geological research is available, the deep ocean basins will remain beyond ready access to most of the US science community. As for subduction zones, recent advances in our understanding of the walls of deep-sea trenches and the effects of subduction of oceanic lithospheric plates are the result of dives with foreign submersibles in these areas.

Marine geological physical and geochemical research in the last ten years has concentrated on three principle areas: 1) formation and growth of the oceanic lithosphere at the mid-ocean ridges, 2) various aspects of deep ocean basins including the processes of maturation of the oceanic lithosphere, the formation of mid-plate volcanic centers, the deformation of the oceanic lithosphere, and sediment distribution in the deep oceans, and 3) effects of subduction of oceanic lithosphere beneath either oceanic or continental lithospheric plates. Marine biological research for diving to > 6500 m is multifaceted, and includes (but is scarcely limited to) environmental impact studies, fisheries research, ecosystem and community function, and biogeography. The types of data required in order to pursue studies in these

research areas are varied and numerous, but there can be no doubt that the impact of *in situ* studies on the marine scientist's ability to understand processes active in the water column and beneath it is profound.

ROV's can provide less expensive access to the deep ocean. However, whereas both are needed, there are aspects of submergence science that can be best carried out with on-site human presence in an occupied vehicle. The critical areas in which occupied submersibles exceed the capabilities of ROV technology are in engagement of the observer, visibility from the platform, maneuverability, the ability to approach targets with stealth, and the capacity for outreach, education, and recruitment of new scientists to the field.

The purpose of the following review is to highlight the aspects of current marine research that would benefit directly from the use of a submersible capable of reaching depths greater than 4500 m, the existing depth capacity for the National Deep Submergence Facility's Alvin submersible.

Ridge Crest and Related Studies

The recent focus of interest on mid-ocean ridge processes has emphasized the advances made by the marine geological community in understanding the processes of formation of oceanic lithosphere. Yet, the community recognizes the continuing need to explore aspects of ridge crest morphology, structure, composition, and associated biosystems that remain poorly understood. Many advances in the understanding of ridge-crest evolution were the result of investigations of seafloor morphology that came about with the advent of side-scan sonar imaging and bathymetry systems, such as the U.S. Navy multibeam systems of the 1960's, and the proliferation of similar and related imagery systems in the 1970's (e.g. Sea Beam, DEEPTOW, GLORIA, SeaMARC I, SeaMARC II, HMR-1 and various commercial systems [e.g., Vogt and Tucholke, 1986]). With detailed data on morphology and results of numerous geophysical and geological research cruises to the ridge crests, it is possible not only to identify those ridge crest regions whose direct exploration with submersibles would most benefit the science, but also to make most effective use of dive time.

Propagating Rifts

Propagating rift tips, where one segment of a ridge crest grows in length at the expense of an adjacent segment, are of particular interest (e.g. Searle et al., 1989). Many tips of propagating ridges are deeper than 4500 m. The composition of the lavas that erupt at the tips of propagating ridges is unusual (Christie and Sinton, 1981). It has been suggested that these lavas are generated as a consequence of the interaction of magmas residing in the magma chambers of the ridge segment with the thick oceanic lithosphere through which the ridge is propagating. The effects of these interactions are likely to be reflected in the distribution, composition, and morphology of lava flows emanating from a ridge tip. The fact that the ridges are propagating into older crust is interesting in itself because fundamental problems of the mechanics of spreading ridge propagation can be addressed through studies of the structures that form in the microplates adjacent to propagators. These microplates show rapidly evolving complex deformation (Searle et al., 1989) and we know little of the details of how these

deformational structures form. The faulting associated with propagation of ridges at these great depths also exposes the transition from oceanic crust to mantle (e.g. Hess Deep), thus the structural interrelationships between the mantle and crustal portions of oceanic lithosphere are accessible (Gillis et al., 1993, ODP Leg 147). Direct observation, mapping, and detailed sampling from submersibles is the most straightforward way to investigate the petrology and structures which will explain these enigmatic ridge-crest features.

Evolution of Oceanic Lithosphere

Petrologists, studying the genesis and evolution of igneous rocks of the oceanic crust and upper mantle, are interested in the details of exposures of sequences of lavas and related rocks in the walls of fracture zones between ridge crests (e.g. Otter Team, 1985; Auzende et al., 1989). These locations expose the stratigraphic and cogenetic relationships between the mantle source rocks and the lavas generated from them that form the upper layer of the oceanic crust. Often exposures of peridotites, which are the mantle rocks that partially melt to form basaltic crustal lavas, occur in these transform fault walls (Dick, 1989). The peridotites are sometimes hydrated by the interaction of seawater with the rocks, creating serpentine, as deformation takes place on the transform faults. The processes associated with the formation of these serpentinite bodies are of great interest to geochemists concerned with the interactions of water and rock and to those geologists concerned with the circulation of seawater through hydrothermal systems of the ridge crests or in the continent–ocean transition region. Sequences of unaltered, coarse-grained, peridotites and gabbros, representing the layers of accumulated crystals at the base of ridge crest magma chambers, are also often exposed (Meyer, et al., 1989). These layered cumulate rocks can help to detail the periodicity of magma injection along ridge segments, the temperature of the magma, its rate of cooling, and its composition as well as that of its source. This information is critical to understanding the evolution of magma chambers at ridge crests.

Sometimes it is possible to study both the magma chamber sequences and the conduits through which the magma reached the seafloor. The systems of feeder dikes that carry these lavas upward can be examined for structure, density of dikes, variations in composition, and degree of alteration if good exposures can be found such as at the Hess Deep. Further, the relationships of lava flows to their feeding dikes can be studied. It is possible then, to study a full suite of the kinds of rocks that compose the oceanic lithosphere in exposures along the transform faults between the ridge crests. The Deep Sea Drilling Project and the Ocean Drilling Program have addressed the problem of layered sequences of oceanic lithosphere for years, but even with the wealth of data amassed through these programs, the spatial relationships between sequences cannot be reconstructed. When we examine exposures of similar sequences of rocks on land we find tremendous variability in structures over short distances. In order to build a model of the formation of the oceanic lithosphere we must combine the results from a variety of data sets, geophysical studies, and drilling studies, and then test them in the field with submersible observations and sampling.

Abyssal Depths in the Ocean Basins

Lithospheric Aging

It is important to recognize that the entire volume of the ocean is cycled through a massive and complex system of plumbing conduits within the seafloor once every million years (IODP Init. Sci. Plan, 2001). The consequences of this dynamic process is to alter the lithosphere, redistribute heat, and provide pathways for the transport of both nutrients and microbial life forms throughout the lithosphere.

There are several interesting aspects of recent marine geological research that focus on the deep ocean basins in abyssal depths. The abyssal depths of the oceans are virtually unreachable by currently available US academic submersibles. But the deep ocean basins are the only place where the maturation of oceanic lithosphere can be studied. There are deep troughs that provide access to great sections of the oceanic crust in the abyssal depths of the ocean basin (e.g., Kings Trough), as well as along the active ridge crest transforms. Whereas transform valleys allow a look at what is happening very early in the formation of the oceanic lithosphere, the deep mid-plate troughs are a potential window onto the aging of the crust. In places like Kings Trough in the eastern Atlantic, west of Portugal (Cann and Funnel, 1967), the Emperor Trough in the western Pacific, etc., it is possible to study composition and structure of the oceanic lithosphere. The Kings Trough has been examined by Soviet scientists using the MIR 6000 m submersible for petrologic and stratigraphic details.

In addition to allowing us to explore the composition of the lithosphere, deep exposures at transforms, fracture zone escarpments, and mid-plate troughs would, if accessible, be of tremendous help in deciphering geophysical observations. Studies show that seismic properties of the upper crust are strongly affected by cracks, fractures, porous layers of breccia, and other void space (Fryer and Wilkens, 1988; Fryer et al., 1990; Moos and Marion, 1990). Lateral variability of seismic structures, as well as age-dependant increase in seismic velocities, is primarily controlled by the degree of cementation and hydrothermal deposition in this void space. So far, the relationships between such large scale porosity and seismic structure have been investigated primarily by appeal to ophiolite sequences (sediments, lavas, feeder dikes, underlying magma chamber sequences, and upper mantle rocks that are exposed on land in many part of the world), by assuming the porosity structure that can be inferred from extrusives in ophiolites are applicable to the oceanic crust in general. However, that approach gives little indication of the age dependence of that porosity. What is desperately needed is direct observation of sections through the extrusives. Submersible investigations of fracture zones and mid-plate troughs are really the only option.

Submersibles will assist in seismic investigations in another way; in the conduct of on-bottom seismic experiments. To measure the seismic structure of uppermost crust demands on-bottom seismic receivers and near-bottom or on bottom sources (Purdy, 1987), especially on young or uncemented crust. A complete understanding of crustal structure will never be achieved, however, until the anisotropic effects of flow layering and tectonically-controlled fractures are also considered. Such studies of anisotropy effects will require tightly navigated arrays of ocean-bottom seismometers and careful deployment and operation of shear-wave sources. Running such experiments would be best conducted using a submersible.

Biodiversity

The transition between the lower continental rise and the abyssal plain between 4000 and 6000 m corresponds to one of the most interesting biogeographic transitions in the ocean's benthic environment. It is also one of the least sampled and most poorly understood. And, of course, it is global in distribution. This is a region where species diversity decreases significantly with depth and distance from land, essentially as an attenuation of the bathyal fauna. In this region, populations of individual species shift from showing depth-correlated clines, both genetic and phenotypic, to being remarkably uniform over huge areas of the abyss. These trends have led to speculation about the causes, but there has been too little precision sampling and experimental work to test them. Indeed, there has been so little abyssal sampling in the World Ocean that no-large scale biogeographic trends are known for depths below the continental margins; bathymetric trends in diversity throughout the depth range from the shelf to the abyss are really known in any detail only for the western North Atlantic. Specifically, the rise-abyss transition is the one region where two hypotheses proposed to account for diversity gradients in the deep sea could be tested experimentally. These hypotheses are 1) that diversity reflects productivity (particularly at these depths where the rate of nutrient input becomes extremely low and populations essentially experience a chronic Allee Effect, and 2) that variability in sediment grain-size affects diversity by limiting (or enhancing) local environmental heterogeneity. Controlled experiments could be used to test these hypotheses. The results of these experiments would be of general interest to ecologists (not just deep-sea biologists) because productivity has risen to the forefront as a general explanation for patterns of biodiversity in terrestrial and shallow-water ecosystems.

Much of what we know about deep-sea ecosystem function comes from the study of continental margins or ridge communities. Vast portions of the ocean floor consist of abyssal plain with depths 4500-5500 m. It has been estimated that as much as two-thirds of Earth's microbial population may be resident deep in oceanic sediment and crust. The new Integrated Ocean Drilling Program has as one of its major research initiatives the further sampling of the deep biosphere with the view toward understanding such problems as how the huge biomass survives in an environment of apparently meager resources. The biochemistry, microbial physiology, and microbial ecology of this population is largely unknown. Clearly, organic and inorganic chemical reactions and geologic processes associated with these populations are all interlinked, but we know virtually nothing about the complexities of these linkages. *In situ*, down-hole laboratories will be established that will require monitoring via submersibles for some of the more intricate and power/lift requirements. The exploration of the deep biosphere has potential for contributing to sources of new materials and for biotechnical applications such as water treatment and microbially enhanced oil recovery. It is clear that in order to assess the extent of this microbial population it will be necessary to determine the nature of microbial populations, pore water chemistry and organic-chemical compositions over varied seafloor depths and in many different environments and tectonic settings. This burgeoning field of microbiology will require experimentation in all of the various settings in which populations are found. The use of a submersible that can access the majority of depths is critical to providing the means by which to perform *in situ* perturbation experiments and deploy observatory equipment that will be needed for this enterprise.

The seafloor portion of the abyssal regions must also be understood for the potential sediment/water exchanges and the ecology of life at this interface. The abyssal ocean basins lie beneath the ocean's most isolated, most oligotrophic regions. Exploration of ecosystems in

these regions, which make up nearly half the sea floor, is certain to yield novel life forms and assemblages. Key questions about the evolution and adaptations of species and function of communities and ecosystems under conditions of extreme isolation and food limitation can be addressed by observational and manipulative endeavors at these depths. Measurements of biogeochemical fluxes will contribute to our understanding of abyssal ecosystem function and its role in global cycles. Abyssal plain ecosystems in this depth range will be the most pristine marine habitats, but there will be inevitable cascading effects of global warming and other anthropogenic modifications. The ability to monitor these changes in the context of atmosphere-pelagic-benthic coupling is critical. Establishment of a long-term, interdisciplinary, abyssal ecological research reserve would provide critical records of global change in the single environment that covers most of the surface of the planet. Does the 'biodiversity crisis' on land extend into the abyss? How do abyssal ecosystems function in the face of loss of diversity? Without monitoring and experimentation, these questions will remain unaddressed.

The ocean depths are used and considered as deep-sea dump sites (e.g., carbon dioxide and high-level radioactive wastes). The impact of proposed dumping and other human activities on the organisms that live on and in the sediments is poorly understood. Climate change may also have a significant influence on deep-sea organisms at depths greater than 6500 m as ocean circulation changes alter thermal conditions and patterns of delivery of primary productivity to the deep seabed and on the structure and function of abyssal communities. While background information on species diversity and biomass can be obtained from surface ships using box-cores and other sampling gear, experimental approaches that manipulate conditions to approximate anticipated changes to examine species-specific or community-wide responses to the experimental treatment require submersible capabilities. If fisheries exist or could be developed for species that live at greater than 4500 m, then it will be imperative to use submersibles to study species' habitat, foraging and reproductive behaviors, and the effects of fisheries activities on the habitat and the organisms. Our knowledge of the autecology of any abyssal or hadal species is meager.

Ocean current and internal waves activity

Instruments lowered from ships serve to collect much of the data necessary for understanding the interactions of ocean currents and the physical processes involved in transport of large water masses within the water column and on the ocean floor. The marine sciences community is, however, on the road to building a network of underwater observatories for sustained monitoring and the conducting of experiments *in situ*. Most of the engineering and maintenance of these observatories can be done from the surface with ROV or other technology, but some experiments and the placement of large components of underwater observatories may require occupied submersibles. These observatories will be required in a variety of settings on the deep ocean floor and it would be necessary to have a submersible capable of greater than the current 4500 m.

Occupied submersibles would provide some key sampling capabilities for collecting water samples to connect physics with biogeochemistry. The occupied submersible is better able to perform precise placement of sampling devices relative to specific flows or other oceanographic/topographic features on the seafloor because of the better perception capability

from a submersible with an observer *in situ*. Submersibles can permit co-located physical and biochemical measurements that are needed in relation to the venting activity.

There are some locations where intense internal flow results from channeling of bottom water circulation through narrow topographic features. To study the structure of those flows and the turbulence generated would benefit in some ways from submersible-based study. We have learned that internal waves (especially at tidal frequency) are a major source of turbulence in the deep ocean. Whereas some aspects of these processes have been studied in relatively shallow water near landmasses, we know virtually nothing about these processes at abyssal depths. The generation of these waves at steep topographic features (e.g., fracture zone traces, scarps within deep ocean trenches or on the seafloor or outer trench rises) and the breaking of such waves as they encounter other steep features has the potential to influence large scale movement of water masses in the deep oceans. Investigating these processes would be best studied with arrays of precisely positioned sensors. Such sensor arrays must be deployed at locations with carefully determined interrelationships. The sort of deployment necessary will require *in situ* operations possible only from a deep submersible.

Mixing of heat in the oceans

A critical unknown in physical oceanography is the mechanism by which heat is transferred to depth in the water column. There is not enough turbulence in the oceans to account for the degree of mixing that fits observed temperature profiles. It is difficult to study the cooler temperature regions of the water column because the isotherms do not outcrop until high latitudes. It is suspected that topographic effects and tides may account for some of the mixing, but it is difficult to measure these types of effects with existing technology. Whereas AUVs will be useful for general mapping, what would be ideal is to measure physical conditions at depth in the water column along contour (both topographic at a given geologic feature and thermal within the water column). This sort of measurement could be readily accomplished using a probe mounted ahead of an advancing deep occupied submersible. Because the entire water column is involved an occupied submersible with abyssal depth capabilities is necessary.

Mid-plate Volcanism

Studies of mid-plate volcanoes in the ocean basins, and of their underlying "hot spot" sources, have focused on investigations of subaerial lava flows, dredged samples, and on the general structures of the oceanic plate in the vicinity of the volcanoes. The best studied of these volcanoes are those associated with the Hawaiian hot spot. For many of the volcanological problems related to these volcanoes, the depths accessible to 4500 m submersibles would be quite adequate. Studies of the abyssal depths surrounding these volcanoes, however, indicate several exciting phenomena that are only accessible to submersibles having greater depth capability. Massive landslides blanket the slopes of the Hawaiian Islands (Moore et al., 1989), reaching depths of over 5500 m. These slides were almost certainly shaken loose by large tectonic earthquakes (as opposed to earthquakes related to volcanic activity) and have created exceptionally large tsunamis (Moore and Moore, 1984; Fryer, 1996; McMurtry et al., 1999; 2002). The pelagic sedimentation rate is well known. With a deep submersible one could measure sediment thickness and provide an independent verification of the slide dates. The

important thing would be to observe the environment from which push cores are taken. The age relationships of the slide deposits and their morphology could be studied to help to determine the frequency of the slides and the potential for hazard to the populated areas of the islands. Dating of organic debris entrained in the slides, for example, could be used to establish the repeat period of large earthquakes, in much the same way that turbidites in the Cascadia subduction zone have been used to determine earthquake repeat times.

Presumably, the phenomenon of massive slides is common to all mid-plate volcanoes and would be of interest to populated islands all over the ocean basins. For example, Cumbre Vieja Volcano in Canary Islands was recently suggested by Ward and Day, (2001) to be a future site of a massive slide that could endanger the eastern coast of the US. Little is known of the deep flank processes of such sites and of the effects of and distribution of submarine landslides in these environments and yet the potential for harm to coastal regions is predicted to be significant.

Another phenomenon of interest in the vicinity of Hawaii is the occurrence of young volcanic features on the Hawaiian Arch. The Hawaiian arch is that part of the lithosphere surrounding the Hawaiian Island chain that is uplifted as a result of buckling of the oceanic plate in response to the mass of the islands. The arch is in depths of 4 to 5 kilometers. GLORIA side-scan sonar surveys around the islands, particularly north of Kauai and Oahu, have discovered vast areas of highly reflective material (Holcomb et al., 1988; Lipman et al., 1988). These areas are formed by recent lava flows (Detrick et al., 1988). The lavas are derived from a source similar to that which feeds the mid-ocean ridges, rather than to that which feeds the Hawaiian volcanoes (Detrick et al., 1988), yet, there is no mid-ocean ridge in the vicinity. The lava flows are apparently interlayered with the debris slide deposits from the flanks of the islands (Holcomb et al., 1988). Dating of the volcanism and the slides would be possible with a carefully detailed sampling program. The variety and complexity of the volcanic constructs associated with these fields of lava is surprising. Side-scan sonar imagery of the fields reveals low shield volcanoes, domes, cratered cones, and a variety of vent types, single vents and linear chains of smaller vents and/or fissures (Holcomb et al., 1988). Detailed studies of the morphology of these lava flows, edifices, and vents might provide clues as to the ultimate origin of the volcanism that produced them. These lava flows, the deepest known extensive fields of flows anywhere, provide a unique opportunity to better understand the effects that composition and pressure differentials have on the morphology of flows erupted on the seafloor. Such studies would require the use of a submersible. It is possible that the deformation of the Pacific lithospheric plate in the vicinity of the Hawaiian arch is related to the formation of the lava fields. What is that relationship? How do the structures of the 80 million year old Pacific plate on which the Hawaiian volcanoes is superimposed affect the distribution of the lava flow fields? Are these volcanic fields still active? The answers to these questions also can be best addressed with detailed investigations using deep submersibles. By studying the phenomenon of near arch volcanism around Hawaii it would be possible to gain critical information regarding the origin, growth and evolution of mid-plate volcanism and regarding the workings of hot spots.

The prospect of development of hydrothermal systems in regions of abyssal-depth, mid-plate volcanism holds promise of unique environments for biological systems. The colonization of such systems, the linkages to deep biosphere activity, and the potential affects of temporal variability in the nature of this volcanism would be of interest to a wide variety of marine

biologists. The development of fisheries in association with mid-plate seamount evolution could be best determined with the stealth capability of an occupied submersible at all depths.

Convergent Plate Margins

The effects of subduction of the oceanic lithosphere beneath both continental and oceanic lithospheric plates are the targets of recently focused interest in the marine geological community (Raleigh and Sclater et al., 1989). While we have amassed a great deal of information regarding subduction of lithospheric plates, subduction phenomena represent an aspect of the formation of the earth's surface that we have never been able to study systematically in detail. Deep ocean trenches, many in excess of 6500 m, preclude investigation with any of the existing submersibles.

The simple case of subduction of a relatively featureless oceanic plate beneath another relatively featureless oceanic plate hardly ever happens. Most convergent plate margins are complicated by various structures on both plates. The three important components of any subduction system are: 1) the oceanic plate and the major structures of which it is comprised; 2) the forearc area, that part of the convergent zone between the trench axis and the active volcanic arc; 3) the volcanic arc; and, in the case of many interoceanic convergent margins, 4) active seafloor spreading processes in the area behind the active volcanic arc, the so-called "backarc basins."

Incipient Subduction Zones

How is subduction initiated? The only place where we could look to find an incipient subduction zone would be in the abyssal depths of the ocean basins. Are there any candidates? The western Pacific may have one. Many earthquakes in the Western Pacific cause substantial ground motion and generate local tsunamis, but go undetected by the world-wide seismic network. Because these earthquakes are located within the oceanic plate, their seismic energy propagates very inefficiently to stations of the network, which tend to be concentrated on the continents, across the convergent plate boundaries at the margins of the Pacific. If less than a certain magnitude, the energy from these earthquakes is not propagated across these plate boundaries and the earthquakes are not detected on the network (Walker and McCreery, 1985; 1988). Such earthquakes were, however, detected by hydrophone arrays in the Pacific. Epicenters of these "unreported" earthquakes define a zone stretching from south of Guam, past Ponape, and further southeastward (Kroenke and Walker, 1986). The small number of these earthquakes detected by the world-wide net all have thrust mechanisms, suggesting that the Pacific oceanic plate is being thrust down under the southwestern Pacific. The implication is that subduction is being initiated all along this zone creating a new trench (Kroenke and Walker, 1986). There is morphological evidence from geophysical profiling in the vicinity of the earthquake zone that supports the new trench hypothesis. The existence of a newly forming trench is one of the most exciting and controversial discoveries of recent years. If the zone of earthquakes and the features observed in geophysical surveys of the region are indeed effects of a newly forming trench, we have available to us the first natural laboratory for the study of the processes of the earliest stages of subduction. We know very little of how trenches form and how plate subduction is initiated.

Several *in situ* experiments could be run to examine the structures and processes related to earthquakes associated with such an hypothesized incipient trench. These experiments might allow the first glimpse of the incipient stages of formation of convergence plate margins. It would be possible to deploy arrays of ocean bottom seismometers to monitor low-level earthquake activity and thus to examine the interaction of the two converging plates. It would be possible to set up experiments to study the structures indicative of the early stages of deformation within the new trench. It would be possible to study details of the escape of fluids from deep sea sediment, a common phenomenon observed on convergent margins of oceanic plates (e.g. Kulm et al., 1986). Venting of fluids at convergent margins is a phenomenon of global proportions about which we know very little. Marine geologists are interested in determining the nature of the escaping fluids in order to study the cycles of a variety of constituents of these fluids that are part of the global budgets of various elements. The cycles of these elements carry implications for global patterns of tectonic processes, volcanism, and even climatic change. Unfortunately, the hypothesized new trench lies at depths beyond the reach of a 4500 m submersible.

The Subducting Plate

A variety of features in the abyssal depths, near the trench axes, beyond the reach of 4500 m submersibles, are of interest to marine geologists. It would be very useful to look at what's going on as the plate bends and fractures immediately before it subsides into the trench. At depths of 5 kilometers and more, there are numerous normal faults in the down-going plate. The offset along the normal faults formed in the oceanic plate is several hundreds of meters, in some cases. Although these exposures would not reveal the deep structure and composition of the oceanic plate, they would provide access to deep sections within the sedimentary column on the plate, and provide the opportunity to study the stratigraphy of the sediments near trench axes, some of which blanket the oldest oceanic crust in the world. The deformation of the down-going plate also raises questions concerning the fate of sediments near and within the subduction zone. Recent detailed mapping of the down-going plate outboard of the Challenger Deep shows massive submarine landslide regions and development of mud volcanoes on the down going plate as it nears the trench axis (Fryer et al., submitted). This data suggests that the dynamics of sediment redistribution on the subducting plate is a process that we know next to nothing about. The nature of sediments on the descending plate is important to our understanding of the physical constraints on seismicity within the subduction zone and of the nature of reactions that take place within the outer tens of kilometers of the forearcs of convergent margins (where most of the fluids from the subducting-plate are released).

Forearc Regions

There are two different types of convergent margins, those associated with the transfer or "accretion" of oceanic material from the downgoing plate or from along trench sediment transport onto the overriding plate, and those where the igneous and metamorphic basement of the overriding plate is exposed directly on the inner slope of the trench, where the overriding plate is being eroded away by tectonic processes associated with subduction of the downgoing plate. In accretionary margins the transfer of material from the descending to the overriding plate

or the transport of material from adjacent land exposures results in the build up of great wedges of sediment and slivers of oceanic crust in the forearc region. It is important to our understanding of evolution of accretionary margins that we be able to make detailed studies of the constituents of the wedges and of the geologic processes taking place on the seafloor that allow us to understand the phenomena occurring deep within the wedges. For instance, sediment transport across the downgoing plate would be ideal for study by submersibles. In what directions and how fast does sediment move across the downgoing plate? How is the sediment transport influenced by the growth of the accretionary wedge in such plate margins? These accretionary prisms are not static. As they grow and evolve, the accumulated sediments are subjected to changes in temperature, pressure, and stresses. Several researchers have studied of the dynamics of accretionary wedges (e.g. Barr et al., 1989; Hoffmeister et al., 1989) and have discovered that as the wedge evolves, routes for the migration of various constituents of the wedges are established and these routes can, at least theoretically, be predicted. As biogenic components in the sediments are distilled into hydrocarbons, the wedges become sites of hydrocarbon formation, including gas hydrates, and seeps of pore fluids that are observed in many of the convergent plate margins around the world could be monitored using deep submersibles. In this manner the nature of the transport of hydrocarbons through the accretionary wedges could be studied.

Many of the important subduction zone decollements and other key fluid conduits occur at depths greater than 4500 m. In order to instrument them and carry out experiments we need a submersible with a greater depth capability than Alvin currently has. For example, at Barbados it was necessary to use the Nautilo to instrument the ODP CORKS, etc. The science of seafloor monitoring and perturbation experiments is rapidly developing. In addition, the Ocean Drilling Program has installed more CORKS in different parts of the ocean, including at depths >4500 m, especially in subduction systems and older ocean basins. They are installed as legacy holes for long-range hydrological and microbiological experiments in the sub-seafloor for the up-coming Integrated Ocean Drilling Program and are not limited artificially at 4500 m. The new frontier of science of unraveling the hydrology, geochemistry, and microbiology of the "ocean below the seafloor" depends on such a capability. Recent (Leg 195) drilling on a serpentine mud volcano on the outer half of the Mariana forearc recovered archea in an extremely high pH environment within the active conduit of the mud volcano (Mottl, et al., submitted). This unique setting for these microbes underscores the potential to find new environments wherever active fluid egress is found.

Subduction zones are dynamic regions where biological communities are likely to be altered by mass sediment movement, tsunamis, tectonic activity, and hydrocarbon seepage. A capability to use occupied submersibles at trench margins will allow us to understand the consequences of large-scale disturbance, high pressure and alternative carbon sources in the deep sea. Alvin dives at 4445 m depth on the edge of the Aleutian trench revealed assemblages of animals unexpectedly reliant on methane-derived carbon (up to 50%) (Levin and Michener, in press). At greater depths this reliance may become even more extreme and precision sampling in appropriate environments could yield discovery of novel microbial-animal interactions. A comparison of trench biota under conditions of markedly different productivity (Peru/Chile, Aleutian, Cariaco, Puerto Rico, Mariana) would yield tremendous insight into the coupling (or decoupling) of surface processes and tectonic processes influencing deep-sea ecosystem.

The problem of slope stability of regions adjacent to accretionary convergent margins (and passive margins) is of concern for potential hazard mitigation efforts. We know that major landslides have occurred in the forearc regions of many convergent margins. Those of the Aleutian arc for instance have repeatedly sent devastating tsunamis across the Pacific to destroy coastal areas of Pacific islands and the coasts of the Pacific rim. Understanding the factors that cause slope destabilization and the mechanisms by which these landslides take place and generate tsunamis is little understood at present. The toes of many of these slides, where the first motion takes place are in depths in excess of 4500 m and in some cases the distal edges of the slides ride over the trench axis and on-lap the descending plate. To map these distal portions of the slides and sample materials that could be dated we would need a submersible with greater depth capability.

Sediments in nonaccretionary convergent margins are derived from the adjacent continental land mass or from the adjacent oceanic arc volcanoes. The transport mechanisms of sediments may be quite different in non-accretionary margins. For example, skeletons of delicate, shallow water foraminifera (carbonate secreting, one-celled organisms) have been recovered from cores taken from greater than 6000 m depth in the Peru-Chile Trench (Coulbourn and Moberly, 1977). These skeletons had to have been both transported to the deep trench sites and then buried rapidly, otherwise, they would have been destroyed by dissolution in the deep, cold waters. The rapid transport of sediment across the South American overriding plate margin presents a number of problems. What's the mechanism of this transport? Is it related to the process of tectonic deformation of the outer edge of the plate? If so, how? What structures influence the distribution of sediments and how? We can answer part of some of these questions already. Complex channels have been discovered using side-scan sonar imagery and bathymetry of the South American plate margin (Bartlett, 1987). The results of investigations of cores taken from near these channels indicate frequent large volume transport along the channels. Detailed studies of sediment distribution within the channels would facilitate understanding the mechanism and rates of transport of the sediments. Such studies could only be undertaken with deep submersibles.

The non-accretionary convergent margins also provide the opportunity to investigate directly the interactions between the outer toe of the forearc and the subducting plate. As the down-going plate bends and fractures the stresses being imposed on the plate also disrupt ridges and seamounts that are riding the plate down. Several studies have shown that the seamounts on the down-going plate are severely deformed as they are subducted (Fryer and Smoot, 1985; Yamazaki and Okamura, 1989). As ridges and seamounts are subducted they uplift the inner toe of the forearc, producing vertical tectonic deformation over a region at least as large as the feature being subducted. Other structural changes may also occur as the subducting feature, interacts with and disrupts the brittle outer toe of the overriding plate. Clearly, the additional disturbance caused by the subduction of a large ridge or seamount could accelerate the erosion of the outer edge of the overriding plate. The walls of forearc grabens expose thousands of meters of crust (Hussong and Fryer, 1985; Johnson and Fryer, 1990). These exposures provide an exceptional opportunity to explore the structures and composition of forearc crust and upper mantle using submersibles (Fryer et al., 1995). For example, in the case of the Mariana forearc, dredge hauls had until recently yielded only rocks that are related compositionally to the kind of magmas that produce the active islands of the adjacent arc

(Bloomer, 1983). Unfortunately the walls all of the Mariana forearc grabens, are in depths greater than 4500 m, and thus beyond the reach of existing US submersible capability.

As the downgoing plate descends beneath the forearc wedge, the increasing pressure and temperature to which the subducting plate is subjected distill from it a variety of fluids. The first fluids to be driven off the downgoing plate are from pore spaces in the unconsolidated oceanic sediments. As the plate descends further fluids are pressed from cracks in the consolidated sediments (sedimentary rocks), the altered, crustal lavas and the deeper crustal rocks. With increasing pressure and temperature, dehydration reactions in the deep crustal and upper mantle rocks release fluids. All of these distillates must escape from the downgoing plate. Some rise along the boundary between the two plates. Evidence for the escape of such boundary fluids can be seen in the axis of the trenches as disturbed sediments and hummocky topography on the seafloor, and the fluids themselves can be detected in the composition of deep bottom waters. Some of these fluids escape through the overlying forearc wedge along fault traces. These fluids are highly reactive and their passage through the overlying rocks significantly alters or metamorphoses the rocks. It is likely that the effects of interaction between the deep parts of the overriding plate and the fluids being driven off the downgoing plate through dehydration of sediments and altered crustal rocks control the metamorphism of vast regions of the overriding plate.

Submersible studies of two large seamounts on the outer half of the Mariana forearc demonstrate the effects of such metamorphism and the utility of submersible studies of such features (Fryer and Fryer, 1987; Fryer and Mottl, 1997; Fryer et al, 2000). These are mud volcanoes but far larger than sedimentary mud volcanoes like those of Barbados (Brown and Westbrook, 1988). Unlike sedimentary mud volcanoes, however, the Mariana forearc mud volcano was formed by repeated cold protrusion of flows composed of fine-grained serpentine (Fryer, 1992; Fryer et al., 2000). Movement along deep faults probably triggers the protrusion events. Slab-derived fluids with very high PH (12.5^+), low chlorinity, and high methane contents (Mottl, 1992) find routes of escape from depth. Where these fluids escape to the surface along deep forearc faults they carry the comminuted serpentinite up along with them to form serpentine mudflows on the seafloor (Fryer, 1992). Repeated eruptions over tens of millions of years resulted in the formation of the seamounts. Deep sea drilling of two such seamounts recently provided supporting evidence for this interpretation (Scientific Shipboard Party, ODP Leg 125, 1989a and b, Initial Reports ODP Leg 195). Both drilled seamounts are still active. Seismic studies of them could depict current activity, however the magnitude of any seismic activity associated with this seamount is probably quite low because the flow materials are so ductile. A very carefully controlled series of seismic experiments to examine the natural seismicity of the seamount and to run small scale seismic refraction studies would allow us to examine both the activity and fine internal structure of the seamount. Such experiments would require deployment of bore-hole and ocean bottom seismometers on the seamount and around its base. The continued study of these seamounts is severely constrained by the fact that their flanks and bases are beyond the reach of 4500 m submersibles. Without deeper capability the kinds of studies which submersibles would allow us would be impossible.

Several forearc regions are highly deformed, and afford the opportunity to study interactions between rifting and subduction (northern Tonga, Scotia, Southern Mariana). Cross-arc/forearc fault zones could provide the opportunity to investigate sites of fluid egress across the entire range of depth-dependant reactions that must be taking place in the descending

slab at these various convergent plate margins. To be able to collect the highly controlled push cores and rock samples one would need to investigate this possibility one would require an occupied submersible. The depths of the outer forearc fault zone exposures are, however, in excess of 4500 m.

Arc and Backarc Regions

The island arc volcanoes of the interoceanic convergent margin systems are generally shallow features and are well within the reach of 4500 m submersibles such as the Alvin. A great volume of the active volcanism associated with many arc systems, however, takes place within spreading rifts behind the volcanic arc, in the backarc environment. Studies of ophiolite sequences exposed on land in many part of the world indicate that many such sequences were probably formed in arc or backarc basin environments. These portions of crust and mantle are emplaced as slivers or large masses of exotic terranes within the convergent margins of many continental blocks. Thus, they contribute to the growth of continents. Apart from the purely scientific objectives of studying these exotic terranes, they are important as potential reserves of a variety of economically valuable ores. Clearly, the slivers of forearc wedges may be important as sources of oil and natural gas. Also the remnants of the island arcs and backarc basins may contain rich sources of various metallic ores. In order to learn how to predict where these resources might be found, a well-conceived model of the formation of arc and backarc basin crust must be developed. The research necessary to formulating such models can only be carried out in the active counterparts of the exposed exotic terranes, that is, in active arcs and in backarc basins. Some information concerning the nature of submarine volcanism and the development of ore bodies associated with these arcs can be gleaned from the study of the hydrothermal systems of active arc volcanoes (Vonderhaar, et al., 1987; Urabe et al., 1987). These studies can be accomplished with shallow submersibles for the most part. In order to investigate evolution of the backarc basins, however, a deep submersible would be required. Many segments of the active spreading ridges in backarc basins are deeper than is accessible by a 4500 m submersible. Fault bounded grabens occur both within the active volcanic-tectonic zone of backarc basins, and adjacent to the basin-bounding faults of some (Fryer et al., 1997). These bounding grabens expose well over 5000 m of relief and reach depths in excess of 6000 m in some cases. These deep grabens are the best places to investigate the developmental history of island arc lithosphere.

An excellent example of the kind of results that would be expected from studies of the ridge segments of active backarc basins are the studies of one section of the Mariana backarc basin using the Alvin submersible at 18°N (e.g. Craig et al., 1987). The observations show this segment to have many of the same features as mid-ocean ridge segments. However, as one would expect, the backarc basin volcanism is strongly influenced by the tectonic evolution of the arc system. Furthermore, the generation of the magmas that feed the backarc basin spreading centers is strongly influenced by the infusion of the mantle source regions with constituents distilled off the downgoing oceanic plate (Fryer et al., 1981; Sinton and Fryer, 1985). The results of the Alvin dive series demonstrate that the backarc basin spreading center is different in structure, composition, and in the nature of the biological communities associated with hydrothermal fields on the ridge axis (Lonsdale and Hawkins, 1987; Hawkins et al., 1990; Volpe et al, 1990, Kusakabe et al., 1990; Hessler, et al., 1987). These findings indicate that

the mere 50 km segment of the Mariana backarc basin spreading center studied has an extremely variable structure and composition. These variations are intriguing and demonstrate the need to explore other portions of the ridge crests in backarc basins before these spreading centers are sufficiently well-understood to enable marine geologists to construct a reasonable model for the formation of backarc basin crust. Such studies would require deeper submersibles.

Deep back-arc basins appear to support reducing communities that are distinct from those at ridge axes. Those greater than 4500 m have not been explored but must certainly hold surprises that can best be studied by manned submersibles. In general, biological studies benefit from direct (visual) observation, the ability to collect specimens in a specified and known context, and the ability to manipulate and resample organisms.

Conclusions

Studies of mid-ocean ridge processes generally can be addressed with current depth capability with Alvin as most ridge crests lie within the 4500 m depth range. However, the study of propagating rift tips and the stratigraphy and evolution of the oceanic lithosphere will require a submersible with a greater depth capability. In the mid-plate regions the sea floor lies at abyssal depths and thus any geological processes of interest there, such as the problem of lithospheric aging, could only be addressed with a deeper-capability submersible. Studies of biological systems in the abyssal environments will require the precise sampling capability, the ability to map in detail both geological structures and distribution of organisms, and the ability to observe organisms with stealth that can only be obtained from a submersible.

Aspects of mid-plate volcanism, slope stability of volcanic edifices, and the volcanic activity associated with abyssal lava fields could only be studied in detail with a deep-capability submersible. Collection of samples to integrate the physics of movement of currents with the geochemistry of ocean waters in the deep oceans will also require a submersible that can reach abyssal depths. Studies of the actions of currents in response to topographic features (channel induced turbulence and internal ocean waves) would benefit from a submersible approach.

Observatory science and monitoring the oceans long-term and with globally linked observation centers is a goal of all the major fields of ocean sciences in the US. The ability to deliver certain components to these observatories and to run some of the experiments that will be ancillary to the long-term monitoring efforts will require the use of a deep-capability submersible.

The processes of fluid venting and formation of biological communities associated initiation of new trenches in the mid-plate abyssal regions could best be studied with deep submersibles. Deep ocean trenches at convergent margins reach maximum depths of nearly 11000 m and have only been visited in a cursory manner with deep capability vessels such as the Trieste. The new discoveries of active egress of slab-derived fluids, of active serpentine mud volcanoes with attendant unique biological systems, and of complex suites of rocks within the overriding plates in these convergence zones can only be explored fully if a submersible with greater depth capability is available.

The actively spreading backarc basins of convergent margin regions are the sites of production of a unique oceanic lithosphere and form some of the potentially richest reserves of metallic ores on Earth. The study of the formation of lithosphere in these basins is very poorly

understood and without detailed investigations of stratigraphy of lithologic units and an understanding of structures, attempts to develop models that will allow us to extrapolate *in situ* studies to interpretation of subaerial exposures will remain inadequate. In addition, the biological communities that flourish in backarc-basin hydrothermal settings have unique properties. Portions of the ridge crests within these basins are too deep to be accessible to a 4500 m submersible.

The marine geological community supports the development of a deeper-capability submersible (DESCEND Workshop report), and as each new dive series has proven, will continue to make discoveries which further endorse the need to explore in greater depths. Although it is difficult for many modern funding agencies to accept exploration as a scientific endeavor, the fact remains that exploration and discovery provide an exceptionally strong justification for developing an ability to dive to depths greater than 4500 m. The single big lesson from oceanography to date is that as we increase our access to the sea, we discover important new features of our planet and we build on our understanding of their relationship to the larger context. The question is really not why do we want to dive to depths greater than 4500 m; it is rather how could we not want to dive to places we have never been before? If we do not ask this, then we have lost our capacity to imagine the unimaginable.

References

- Auzende, J.-M., D Bideau, E. Bonatti, M. Cannat, J. Honnorez, Y. Lagabrielle, J. Malavieille, V. Mamaloukas-Frangoulis, and C. Mevel, 1989, Direct observation of a section through slow spreading oceanic crust, *Nature*, 337, 726-729.
- Ballard, R. D., and T. H. Van Andel, 1977, Morphology and tectonics of the inner rift valley at 36° 50'N on the Mid-Atlantic Ridge, *Geological Society of America Bulletin*, 88 (4), 507-530.
- Barr, T. D., F. A. Dahlen, and D. C. McPhail, 1989, Modeling metamorphism in actively deforming fold and thrust belts, *Eos, Trans. Am. Geophys. Union*, 70 (43), 1376.
- Bartlett, W. A., 1987, Peru forearc sedimentation: SeaMARC II side-scan interpretation of an active continental margin, Master's Thesis, University of Hawaii, 87 pp.
- Bloomer, S. 1983, Distribution and origin of igneous rocks from the landward slopes of the Mariana trench: Implications for its structure and evolution *Jour. Geophys. Res.*, 88, 7411-7428.
- Brown K. and G. K. Westbrook, 1988, Mud diapirism and subduction in the Barbados Ridge accretionary complex; The role of fluids in accretionary processes, *Tectonics*, 7(3), 613-640.
- Bryan, W. B. and J. G. Moore, 1977, Compositional variations of young basalts in the Mid-Atlantic Ridge rift valley near Lat 36°49'N, *Geol. Soc. Am. Bull.*, 88, 556-570.
- Cann, J. R. and B. Funnel, 1967, Palmer Ridge: A section through the upper part of the ocean crust?, *Nature*, 217 (5077), 661-664.
- Christie, D. M. and J. M. Sinton, 1981, Evolution of abyssal lavas along propagating segments of the Galapagos spreading center, *Earth and Planet Sci. Lett.*, 56, 321-335.
- Coulbourn, W. T. and R. Moberly, 1977, Structural evidence of the evolution of forearc basins off South America, *Can. J. Earth Sci.*, 14, 102-116.
- Craig, H., J. A. Welhan, and D. R. Hilton, 1987a, Hydrothermal vents in Loihi caldera: Alvin results, *EOS, Trans. Am. Geophys Union*, 68 (44), 1553,
- Craig, H, Y. Horibe, K. A. Farley, J. A. Welhan, K. R. Kim, and R. N. Hey, 1987b, Hydrothermal vents in the Mariana Trough: results of the first Alvin Dives, *EOS, Trans. Am. Geophys Union*, 68 (44), 1531,

- Detrick R., J. Sinton, and D. A. Clague, 1988, Volcanism on the Hawaiian flexural arch: Results from Sea Beam, seismic reflection surveying and dredging, *Eos, Trans. Am. Geophys Union*, 69 (44), 1444.
- Dick, H. J. B., 1989, Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism, in *Magmatism in the Ocean Basins*, Saunders, A. D. & Norry, M. J. (eds.), Geological Society Special Publication No. 42, 71-105.
- Fryer, Gerard J., 1996, Hawaiian tsunamis and small submarine landslides, *Eos, Transactions, American Geophysical Union*, 77 (46, Suppl.), 511.
- Fryer, G. J. and R. A. Wilkens, 1988, Porosity, aspect ratio distributions and the increase of seismic velocity with age in young oceanic crust, *Eos, Trans. Am. Geophys Union*, 69 (44), 1323.
- Fryer, Gerard J., Wilkens, Roy H., Karsten, Jill L., Berge, Patricia A., 1990, Evolution of porosity and seismic properties of the upper oceanic crust, AGU 1990 fall meeting, *Eos, Transactions, American Geophysical Union*, 71 (43), p. 1571.
- Fryer, P., 1990, Deep submersibles and potential marine geological research, *Marine Tech. Soc. Journal*, 24(2), 22-31.
- Fryer, P., 1992, A synthesis of Leg 125 drilling of serpentine seamounts on the Mariana and Izu-Bonin forearcs, *Ocean Drilling Program Leg 125, Scientific Results Leg 125*, 593-614.
- Fryer, P., 1993, The relationship between tectonic deformation, volcanism and fluid venting in the southeastern Mariana convergent plate margin, *Proc. JAMSTEC, Symp. Deep Sea Res.* 9, 161-179.
- Fryer, P., 1996, Tectonic evolution of the Mariana convergent margin, *Rev. of Geophysics*, 34(1), 89-125.
- Fryer, P. and N. C. Smoot, 1985, Processes of seamount subduction in the Mariana and Izu-Bonin Trenches, *Mar. Geol.* 64, 77-90.
- Fryer, P. and G. J. Fryer, 1987, Origins of Non-volcanic Seamounts in Forearc Environments, in *Seamounts Islands and Atolls*, *Geophys. Monogr. Ser.*, Vol 43, edited by B. H. Keating, P. Fryer, R. Batiza, and G. W. Boehlert, AGU, Washington, D. C., 61-69.
- Fryer, P. and M. J. Mottl, 1997, Shinkai 6500 investigations of a resurgent mud volcano on the southeastern Mariana forearc, *Research, JAMSTEC Deep Sea Res.*, 13, 103-114.

- Fryer, P., J. M. Sinton and J. A. Philpotts, 1981, Basaltic glasses from the Mariana Trough, in Initial Repts. DSDP, Vol. 60, (Hussong, D. M. and Uyeda, S., eds.) U.S. Govt. Printing Off., Wash., D. C., 601-607.
- Fryer, P., K. L. Saboda, L. E. Johnson, M. E. MacKay, G. F. Moore, and P. Stoffers, 1990, Conical Seamount: SeaMARC II, Alvin submersible, and seismic reflection studies, in Proceedings of the ODP, Part A: Initial Report, 125, 5-14.
- Fryer, P., M. Mottl, L. E. Johnson, J. A. Haggerty, S. Phipps, and H. Maekawa, 1995, Serpentine Bodies in the Forearcs of Western Pacific Convergent Margins: Origin and Associated Fluids, 1995, in *Active Margins and Marginal Basins of the Western Pacific* (B. Taylor and J. Natland, Eds.), AGU Monograph Series, 88, 259-279.
- Fryer, P., J. B. Gill, and M. C. Jackson, 1997, Alvin observations of the Kasuga volcanoes, northern Mariana island arc, *JVGR* 79:277-311.
- Fryer, P., Lockwood, J., Becker, N., Todd, C., and Phipps, S., 2000, Significance of serpentinite and blueschist mud volcanism in convergent margin settings, in *Ophiolites and Oceanic Crust: New Insights from Field Studies and Ocean Drilling Program* (Y. Dilek, E. M. Moores, D. Elthon, and A. Nichols eds.) GSA SPE 349, 35-51.
- Fryer, P., Becker, N. C., Appelgate, B., Martinez, F., Edwards, M., Fryer, G. J., submitted, Why is the Challenger Deep So Deep? Geological Constraints, submitted to EPSL.
- Gillis, K., Mevel, C., Allan, J., et al., 1993, Proc. ODP, Init. Repts., 147, College Station, TX (Ocean Drilling Program).
- Hawkins, James W., Lonsdale, Peter F., Macdougall, J. Douglas, Volpe, Alan M., 1990, Petrology of the axial ridge of the Mariana Trough backarc spreading center, The Mariana Trough; special section, *Earth and Planetary Science Letters*, 100 (1-3), 226-250.
- Hessler, R. R., S. C. France, and M. A. Boudrias, 1987, Hydrothermal vent communities of the Mariana backarc basin, *Eos, Trans. Am. Geophys. Union*, 68 (44), 1531.
- Holcomb, R.T., M. L. Holmes, R. P. Denlinger, R. C. Searle, W. R. Normark, 1988, Submarine north Hawaiian Arch volcanic field, *Eos, Trans. Am. Geophys. Union*, 69 (44), 1445.
- Hoffmeister, A. M., R. E. Criss, and H. W. Day, 1989, Prediction of large-scale fluid circulation in the deep crust from dimensional analysis, *Eos, Trans. Am. Geophys. Union*, 70 (64), 1376.

- Hussong, D. M. and P. Fryer, 1985, Forearc tectonics in the northern Mariana arc, in Formation of Active Ocean Margins, edited by N. Nasu, Terra Scientific Publishing Company, Tokyo, 273-290.
- Johnson, L. E., and P. Fryer, 1990, The first evidence of MORB-like lavas on the Mariana forearc: Geochemistry, petrology and implications for tectonic evolution, Earth and Planet Sci. Lett., 100(1/3), 304-316.
- Kroenke, L.W. and D.A. Walker, 1986, Evidence for the formation of a new trench in the Western Pacific, Eos, 67 (12) 145-146.
- Kulm, L.D., E. Seuss, J. C. Moore, B. Carson, B. T. Lewis, S. D. Ritger, D. C. Kadko, T. M. Thornburg, R. W. Embley, W. D. Rugh, G. J. Massoth, M. G. Langseth, G. R. Cochrane and R. L. Scamman, 1986, Oregon subduction zone: Venting, fauna and carbonates, Science, 231, 561-566.
- Kusakabe, Minoru, Mayeda, Shingo, Nakamura, Eizo, 1990, S, O And Sr isotope systematics of active vent materials from the Mariana backarc basin spreading axis at 18 degrees N, The Mariana Trough; special section, Earth and Planetary Science Letters, 100 (1-3), 275-282.
- Levin, L.A. and R. Michener. Isotopic evidence of chemosynthesis-based nutrition of macrobenthos: The lightness of being at Pacific methane seeps. In Press. Limnology and Oceanography .
- Lipman, P. W., D. A. Clague, J. G. Moore, R. T. Holcomb, 1988, South Hawaiian Arch lava field: newly identified young lava flows on the seafloor near the Hawaiian Ridge, Eos, Trans. Am, Geophys Union, 69 (44), 1445.
- Lonsdale, P. and J. Hawkins, 1985, Silicic volcanism at an off-axis geothermal field in the Mariana Trough backarc basin, Bull. Geol. Soc. Am. 96, 940-951.
- Lonsdale, P. and J. Hawkins, 1987, The geologic setting of hydrothermal vents at the Mariana Trough spreading axis, Eos, Trans. Am, Geophys. Union, 68(44), 1530.
- Macdonald K. C, D. A. Castillo, S. P. Milner, P. J. Fox, K. A. Kastens, and E. Bonatti, 1986, Deep-tow studies of the Vena Fracture Zone, 1. Tectonics of a major flow-slipping transform fault and its intersection with the Mid-Atlantic Ridge, Jour. Geophys. Res., 91, 334-3354.
- McMurtry, G.M., Herrero-Bervera, E., Cremer, M., Resig, J., Sherman, C., Smith, J.R., & Torresan, M.E., 1999, Stratigraphic constraints on the timing and emplacement of the Alika 2 giant Hawaiian submarine landslide, J. Volcanol. Geotherm. Res. 94, 35-58.

- McMurtry, G.M., P. Watts, G.J. Fryer, J.R. Smith, Jr., and F. Imamura. 2002, Giant landslides, mega-tsunamis, and paleo-sealevel in the Hawaiian Islands, *Marine Geology*, submitted.
- Meyer, P. S., H. J. B. Dick, and G. Thompson, 1989, Cumulate gabbros from the southwest Indian Ridge, 54°S-70°16'E: implications for magmatic processes at a slow spreading ridge, *Contrib. Mineral. Petrol.*, 103, 44-63.
- Mevel, C., Cannat, M., Gente, P., Marion, E., Auzende, J.M., and Karson, J. A., 1991, Emplacement of deep crustal and mantle rocks on the west median valley wall of the MARK area (MAR 23°N), *Tectonophysics*, 190, 31-53.
- Moore, J. G. and G. W. Moore, 1984, Deposit from a giant wave on the island of Lanai, Hawaii, *Science*, 226, 1312-1315.
- Moore, J. G., D. A. Clague, R. T. Holcomb, P. W. Lipman, W. R. Normark, and M. E. Torresan, 1989, Prodigious submarine landslides on the Hawaiian Ridge, *Jour. Geophys. Res.*, 94 (B12) 17,465-17,484.
- Moos, D. and D. Marion, 1990, Relationships between elastic-wave velocities and morphology within oceanic pillow basalts, *Earth and Planet Sci. Lett.*, in press.
- Mottl, M.J., 1992, Pore waters from serpentinite seamounts in the Mariana and Izu-Bonin forearcs, Leg 125: evidence for volatiles from the subducting slab. In *Proc. Oc. Drilling Prog., Sci. Results 125*, 373-385.
- Michael J. Mottl, Stephen C. Komor, Patricia Fryer, and Craig L. Moyer, submitted, Deep-Slab Fluids Fuel Extremophilic Archaea on a Mariana Forearc Serpentinite Mud Volcano: ODP Leg 195, submitted to *Science*.
- Otter Team, 1985, The geology of the Oceanographer Transform: The ridge-transform intersection, *Marine Geophysical Researches*, 6, 609-141.
- Purdy, G. M., 1987, New observations of the shallow seismic structure of young oceanic crust, *Jour. Geophys. Res.*, 91, 3739-3762.
- Raleigh, C.B., Schlater, J. G. et al., 1989, Margins: A research initiative for interdisciplinary Studies of processes attending lithospheric extension and convergence, *Proceedings of a Workshop sponsored by the National Research Council, National Academy Press Washington D.C.*, 285 pp.
- Schreiber, E. and P. J. Fox, 1977, Density and P-wave velocity of rocks from the FAMOUS region and their implications to the structure of the oceanic crust, *Geol. Soc. Am. Bull.*, 88, 600-608.

- Scientific Shipboard Party, ODP Leg 125, ODP Leg 125 Plumbs the Pacific Sinks, *Nature*, 339, 427-428.
- Scientific Shipboard Party, ODP Leg 125, ODP Leg 125 drills forearc crust and mantle, *Geotimes*, 34(7), 18-20.
- Searle, R. C., R. I. Rusby, J. Engeln, R. N. Hey, J. Zukin, P. M. Hunter, T. P. LeBas, H.-J. Hoffman, and R. Lovemore, 1989, Comprehensive sonar imaging of the Easter microplate, *Nature*, 341(6244), 701-705.
- Sinton, J. M. and P. Fryer, 1987, Mariana Trough lavas from 18°N: Implications for the origin of backarc basin basalts, *JGR*, 92 (12), 12,782-12,802.
- Urabe, T, M. Yuasa, and S. Nakao, and onboard scientists, 1987, Hydrothermal sulfides from a submarine caldera in the Shichito-Iwojima Ridge, Northwest Pacific, *Marine Geology*, 74, 295-299.
- Vogt, P. R. and B. E. Tucholke, 1986, Imaging the ocean Floor: History and state of the art, in Vogt, P. R. and Tucholke, B. E. eds., *The Geology of North America, Volume M, The Western North Atlantic Region*, Geological Society of America.
- Volpe, Alan M., Macdougall, J. Douglas, Lugmair, Gunter W., Hawkins, James W., Lonsdale, Peter F., 1990, Fine-scale isotopic variation in Mariana Trough basalts; evidence for heterogeneity and a recycled component in backarc basin mantle, *The Mariana Trough; special section, Earth and Planetary Science Letters*, 100 (1-3), 251-264.
- Vonderhaar, D. L., G. M. McMurtry, P. Fryer, and A. Malahoff, 1987, Geochemistry of hydrothermal deposits from active submarine volcanoes in the Mariana arc, *Eos, Trans. Am. Geophys. Union*, 68(44), 1533.
- Walker, D. A. and C. S. McCreery, 1988, Deep-ocean seismology, seismicity of the northwestern Pacific basin interior, *EOS, Trans. Am. Geophys. Union*, 69 (30), 737-743
- Walker, D. A. and C. S. McCreery, 1985, Significant unreported earthquakes in "aseismic" regions of the western Pacific, *Geophys. Res. Lett.*, 12, 433, 1985.
- Ward, Steven N., Day, Simon, 2001, Cumbre Vieja Volcano; potential collapse and tsunamis at La Palma, Canary Islands, *Geophysical Research Letters*, 28 (17), 3397-3400.
- Watts, P., G.M. McMurtry, G.J. Fryer, J.R. Smith, and F. Imamura, 2001. Giant landslides, mega-tsunamis, and paleo-sealevel in the Hawaiian Islands, *Eos, Trans. AGU*, v. 82, Fall Meet. Suppl., F410.

Yamazaki, T and Okamura Y., 1989, Subducting seamounts and deformation of overriding forearc wedges around Japan, *Tectonophys.*, 160, 207-229.