Vol. 3, No. 3

March 1993

GSA TODAY

A Publication of the Geological Society of America

1992 MEDALS AND AWARDS
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Deep Drilling of the Oceanic Crust and Upper Mantle

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ABSTRACT

From the inception of the Deep Sea Drilling Program (DSDP) through to the present investigations by the Ocean Drilling Program (ODP), understanding the processes of generation and aging of the oceanic crust and upper mantle has been a primary objective. Time, technology, and logistics have somewhat restricted the success of these investigations, and it has been necessary until now to rely heavily upon the ophiolite model of ocean crust to provide information on crust-building processes. However, we now realize that many ophiolites, particularly the best exposed and studied, were not generated at major ocean-basin spreading centers but above subducting oceanic plates at convergent margins. In this article, the degree to which ophiolites can help us understand the first order processes of crustal accretion and spreading is reviewed, and a strategy for investigating the lower ocean crust and upper mantle through deep drilling is outlined. This strategy was first tested on Leg 118 in the Indian Ocean, where excellent recovery of gabbroic rocks gave us a preliminary look at in situ layer 3. It was also the focus of drilling on Leg 147 in the Pacific Ocean at Hess Deep in late 1992.

INTRODUCTION

Sixty percent of the present surface of Earth was created at ocean ridges, as magmas generated within the mantle cool to form ocean crust. Over the past two decades, increasingly detailed geological and geophysical investigations of spreading centers, together with field mapping and drilling of a few well-preserved ophiolite complexes, have led to a basic conceptual model for the complex interrelated magmatic, tectonic, and hydrothermal processes involved in the formation of oceanic crust.

The processes whereby ocean crust is created, modified, and destroyed have fundamental implications for the chemical and thermal evolution of the mantle, the buffering of seawater chemistry, and the generation of continental crust. The chemistry and mineralogy of the mantle are influenced by the removal of magmas beneath spreading ridges. Hydrothermal fluxing at the ocean ridges and lower temperature reactions between basement and seawater in older ocean crust control many aspects of seawater composition. Altered crustal rocks play a major part in the nature of volcanism at convergent plate margins, and the net fluxes at these margins have significantly influenced both mantle chemistry and the composition of the continental crust.

Large areas of the sea floor can now be imaged accurately with swath-mapping tools, which have already revealed how the floor of the major ocean basins is segmented. MacDonald (1991) has remarked on how the segmentation is apparent on a variety of scales. First-order segments, usually bounded by transform faults, are generally hundreds of kilometres long and persist for periods of the order of millions of years. They may be subdivided into second-order and even third- and fourth-order segments that become increasingly more transient. Such observations indicate a very orderly spatial and temporal pattern to most sea-floor-building processes, including magmatism, tectonism, hydrothermal activity, and later alteration.

ORIGIN OF OCEANIC CRUST

The oceanic crust of the major ocean basins is formed at oceanic spreading centers. These centers are expressed as the ocean-ridge system, below which the asthenosphere rises to fill the gap between separating tectonic plates. The ocean crust formed in this manner and in this environment has historically been the best studied. However, ocean crust is also formed in marginal basins, peripheral to the major oceans. Although such crust and the processes that formed it are less well studied, we do know that these are somewhat different from those in the major ocean basins. Indeed, it is clear that the production of ocean crust in general is quite variable from one tectonic environment to another and can be produced at spreading rates that may vary by an order of magnitude. Thus, although the development of a general model of the processes that form and alter ocean lithosphere is one priority, in the long term, wide sampling of the observed variability will be required to truly understand the role that ocean crust plays in geochemical cycling.

Our present ideas of the stratigraphy of the ocean crust come mostly from the study of ophiolite complexes, which are fragments of ancient ocean lithosphere. However, for "in situ" ocean crust only a seismic stratigraphy is available, and the seismic data suggest a uniform, worldwide structure. The correlation between typical ophiolite stratigraphy and the seismic model of the ocean crust has been tested at only one location in the oceans, because only one hole (DSDP 504B) has successfully drilled oceanic layer 2B (Becker, Sakai, et al., 1989). Drilling at DSDP Hole 504B has confirmed part

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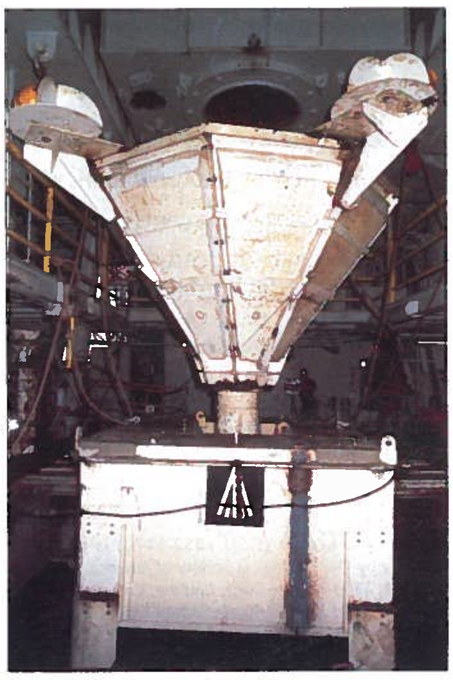

Ocean Drilling Project Hard-rock guide base, used for drilling on bare-rock exposures such as at the mid-oceanic ridge, being readied for deployment on the *JOIDES Resolution*. Bare-rock sites lack the sediment cover of other holes which is used as a guide to hold the drill string and bit steady as it begins drilling into the hard rock. The hard-rock guide base is first placed firmly on the rock surface, and then the drill is guided to the rock by the conical structure.

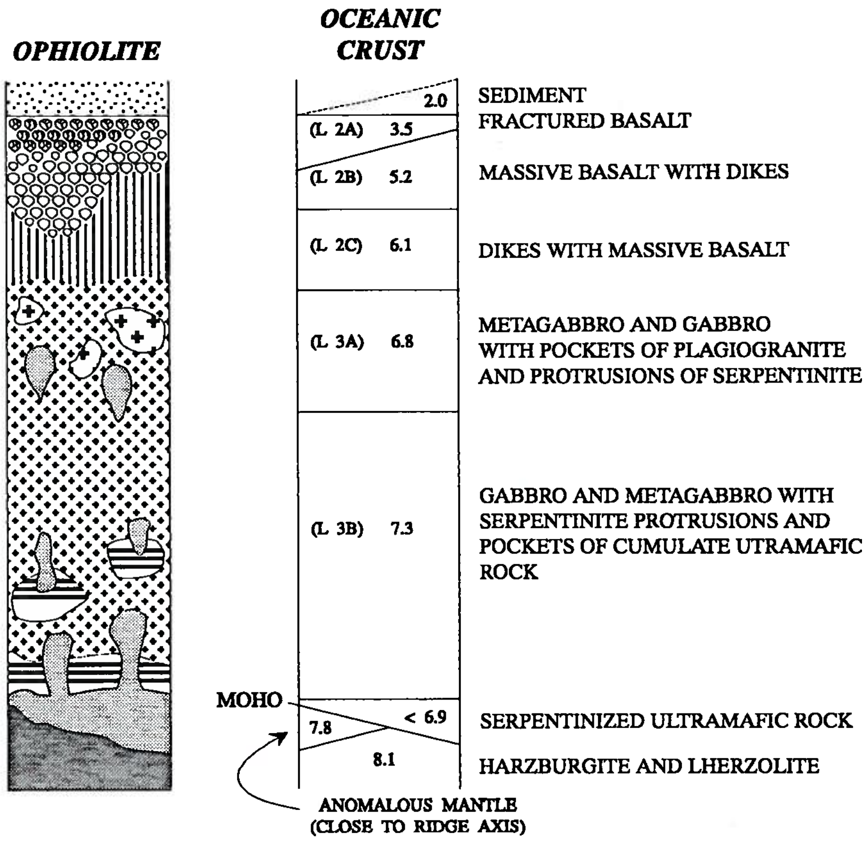

Figure 1. The correlation between seismic stratigraphy of the upper oceanic lithosphere and lithologies observed in ophiolites. L = layer deduced from seismology.

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GSA TODAY *March 1993*
Vol. 3, No. 3

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Second-class postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to *GSA Today*, Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

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of the ophiolite analogue in the form of a pillow-lava carapace overlying a sheeted dike unit (Fig. 1). The correlation of deeper structures of the oceanic crust with that perceived for ophiolites has yet to be verified by deep drilling.

However, the problem of correlation is more profound than this! Recent detailed mapping and drilling programs in several well-exposed ophiolites have shown that the classic layered stratigraphy developed by Penrose Conference attendees in 1972 cannot be universally applied. The best example of this comes from the Cyprus Crustal Study Project of the International Crustal Research Drilling Group (see papers in Malpas et al., 1990), which investigated the Troodos ophiolite.

The Troodos ophiolite is now believed to have formed at spreading axes in a suprasubduction-zone environment resulting from the convergence of the African and Eurasian plates in the Late Cretaceous. Three major suites of volcanic rocks are recognized on Troodos, all of which display geochemical characteristics thought to be related to development from the mantle wedge immediately above a subducting oceanic plate. The rocks show varied degrees of depletion in certain trace elements and preferred enrichment in others, suggesting derivation from a source from which earlier melts had been removed but which had undergone selective addition from fluids emanating from the subducting slab (Fig. 2). The massive sulfide bodies so characteristic of the Troodos pillow-lava sequence are the products of high-temperature hydrothermal solutions that vented on the sea floor along the flanks of axial grabens. Except in the narrow subvertical zones beneath these ore bodies, the Troodos lavas have undergone only low-temperature interaction with seawater. Secondary mineral assemblages consist chiefly of clay minerals, zeolites, and carbonates and appear to have been controlled largely by variations in permeability, lithology, water/rock ratios, and proximity to intrusions. It is the presence of fresh glass throughout the extrusive sequence that has provided an ideal opportunity to study the primary compositional data. This strongly suggests, by comparison with basalt compositions in the present west Pacific, that the ophiolite was produced in a convergent plate margin setting by sea-floor spreading above a subduction zone (Fig. 3). Similar findings apply to most other major ophiolites, which raises the questions, If ophiolites are from environments of formation that are different from modern major ocean ridges, are they sufficient analogues of normal ocean crust, and are the processes that produced the rocks similar in both cases? We must weigh the fact that information we have obtained from ophiolites is still clouded with uncertainty regarding the influence of postformation events, including obduction.

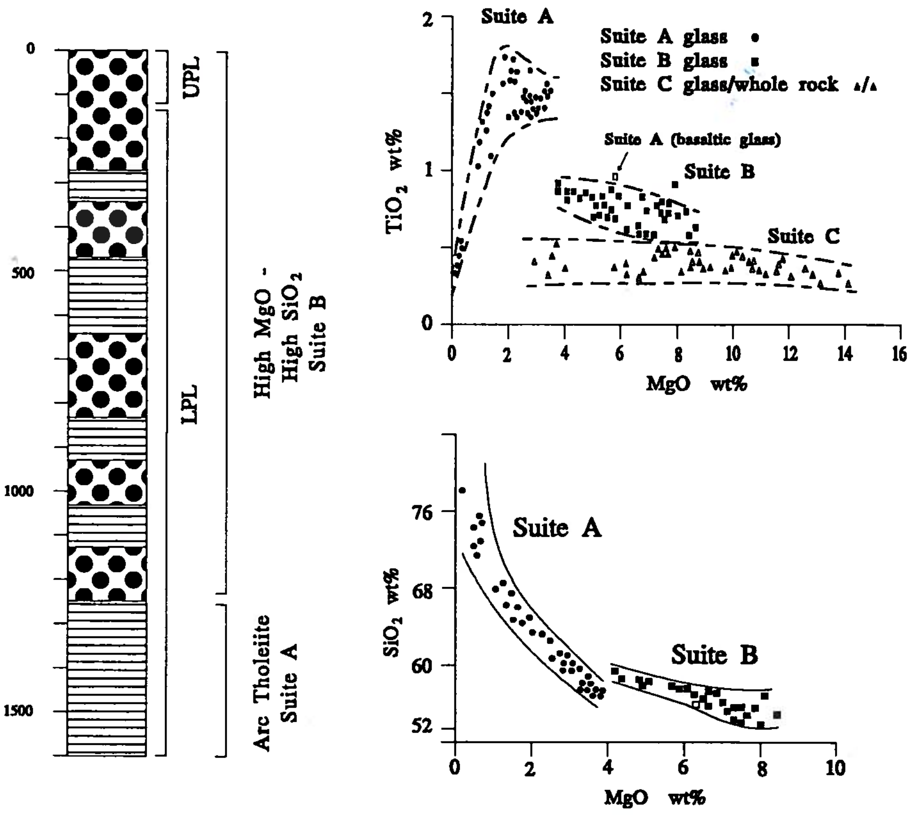

Figure 2. Geochemical stratigraphy of lavas from the Troodos ophiolite, Cyprus. Suite A consists of depleted lavas of island-arc tholeiitic affinity, suite B lavas are more depleted "boninitic" lavas, and suite C is the most depleted Arakapas Fault Zone lavas.

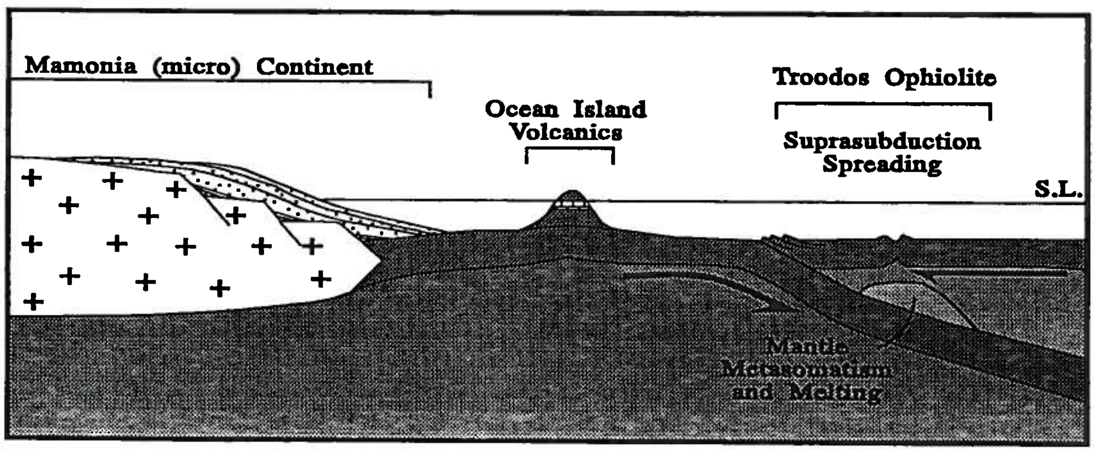

Figure 3. A model depicting the suprasubduction origin of the Troodos ophiolite, Cyprus.

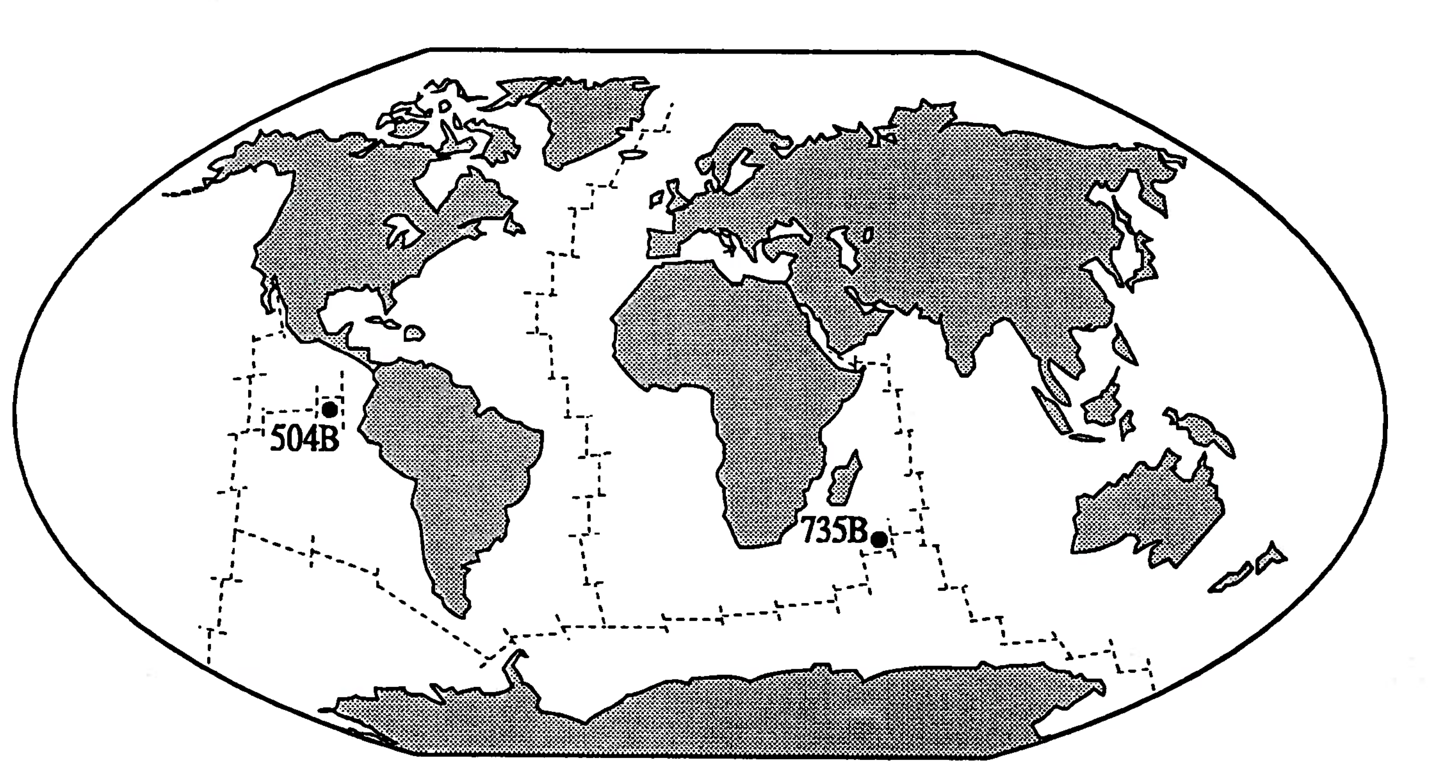

Figure 4. Location of Holes 504B and 735B with respect to the world ocean-ridge system.

INVESTIGATIONS OF THE OCEANIC CRUST BY DEEP SEA DRILLING

In situ igneous ocean crust has been drilled in a great many DSDP and ODP holes. However, in all but a few, the penetration is restricted to the upper few hundred metres of basaltic flows. Two of the more important sites that have been drilled deeper are Hole 504B in the eastern equatorial Pacific Ocean and Hole 735B in the Indian Ocean (Fig. 4).

Hole 504B is the deepest hole into igneous ocean crust. After six legs of drilling (DSDP Legs 69, 70, and 83 and ODP Legs 111, 137, and 139), a total penetration of 2000.4 m below the sea floor has been attained (Fig. 5). One of the initial reasons for drilling on the flanks of the Costa Rica Rift was to examine an area where the ocean crust appears to have reached conductive equilibrium with the young cooling lithosphere, about 5–6 m.y. old.

As of December 1992, Hole 504B extended through 274.5 m of sediment and 1725.9 m into basement. This includes 571.5 m of pillow lavas and minor sheet flows, underlain by a 209 m transition zone of breccia, pillow lava, thin flows, and dikes, and 845.4 m of sheeted dikes. The mineralogy and chemistry of the dikes in the deeper section are nearly identical to those of the overlying lavas and imply crystallization from a magma produced by partial melting of a slightly depleted mantle source. The paucity of glassy, chilled margins deeper in the section and the increase in coarser grain sizes at the bottom of the hole suggest that the sheeted-dike–gabbro boundary lies not far beneath the depth drilled, if the ophiolite model is to be believed. The lower dike section in Hole 504B has been altered as a result of interaction with seawater, and the secondary mineralogy is consistent with the changes that take place toward the base of the sheeted-dike complex in several ophiolites. Many of the lithologic units described from the core at this level contain a variety of gabbroic "clots" that are visible in hand specimen as well as in thin section. Some of these clots contain up to 20% Fe-Ti oxide minerals and are interpreted to be crystallized pockets of trapped Fe-Ti–rich magma. Accompanied by changes in physical properties, including a marked increase in density, these lithologies may herald the transition between layers 2 and 3.

A vertical seismic profile experiment conducted in Hole 504B during Leg 111 records a weak reflector at depths of 1660 to 1860 m beneath sea floor (mbsf). This reflector had earlier been interpreted as the seismic layer 2-3 boundary. However, drilling on Leg 140 penetrated this depth interval, and the reflector is clearly not the transition from dikes to gabbros at Site 504B. It is more likely that the observed changes in intensity of alteration and in physical properties may have caused an impedance difference at about 1750 mbsf which resulted in the observed reflector. Hole 504B has reached the lower part of the sheeted-dike section.

Hole 735B on the southwest Indian Ridge was successful in penetrating unaltered gabbros from presumably the upper part of oceanic layer 3 (Fig. 6). Most of the 500 m section sampled by Hole 735B consists of a single olivine gabbro intrusion that exhibits only minor cryptic variation (Von Herzen, Robinson, et al., 1991). This body appears to have intruded a coarse gabbro-norite at the top of the section and has itself been intruded at the bottom of the section by troctolites and troctolitic gabbros. Numerous crosscutting microgabbros represent melts that migrated through the olivine gabbro prior to its complete solidification. Textural and mineralogical variations in the gabbro section are consistent with its formation in the mush zone that might have surrounded a small crustal magma chamber. The southwest Indian Ridge is spreading at the rate of 0.8 cm/yr, comparable to the slow-spreading Mid-Atlantic Ridge. It is predicted that, where present, the magma chambers underlying such ridges are very small, perhaps less than 2 km wide. Generation of the plutonic rocks sampled at Hole 735B in a small magma chamber might explain their poor layering, limited mixing of magma types, and considerable fractionation. The 735B section has probably sampled the upper parts of oceanic layer 3, although there is no absolute way to ascertain this. Thus, one fundamental problem that remains to be addressed by ocean drilling is the nature of the lowermost oceanic crust.

MAGMA CHAMBER MODELS

Crustal accretion by magmatic means requires the presence of a molten zone or magma chamber(s) beneath the spreading axis. In such chambers the magmas undergo a variety of differentiation processes before their eruption onto the sea floor. In this way, Earth's temperature is controlled, because the magmas provide the energy source driving the hydrothermal circulation that cools the crust.

One outcome of ophiolite research in the past decade is that we can now determine some constraints on the physical nature of the magma chambers that formed these complexes. For example, results from the Cy-4 core of the Cyprus Crustal Study Project show that the layered rocks of this part of the plutonic complex were not produced in a single, large, well-mixed magma body, but from a series of poorly mixed magma pulses injected into a chamber. Additional field evidence demonstrates that this was only one of many independent chambers from which the crust was formed (Fig. 7). This may indeed be the case for the Troodos ophiolite, but studies of other complexes have resulted in a variety of magma-chamber models. In most of these, the magma chamber is viewed as a relatively large molten body that undergoes periodical replenishment, fractionation, emplacement higher in the crustal structure, and eventual eruption. These models seem appealing in that they might be applied to "in situ" ocean crust to explain the relatively simple stratigraphy inferred from seismic studies. However, it is now apparent that they do not fit the most recent findings from the ocean basins, where geophysical results limit the potential size of crustal magma chambers to volumetrically small bodies. For example, seismic data indicate that the crustal magma chamber along the northern part of the East Pacific Rise is less than 1 to 2 km wide and no more than a few hundred metres thick (Sinton and Detrick, 1992). This melt zone is probably surrounded by a mush zone of significantly greater magnitude which is presumably bordered by some form of "cracking front," where cooler solid material is intruded by the melt. Similarly sized bodies likely exist along the southern East Pacific Rise, but at shallower depths below the sea floor. No comparable geophysical data have been collected for the Mid-Atlantic Ridge despite a large number of seismic experiments. Results from seismic reflection and refraction experiments and microearthquake and teleseismic studies appear to rule out the possibility of a large-scale magma chamber, although small, localized bodies could be present.

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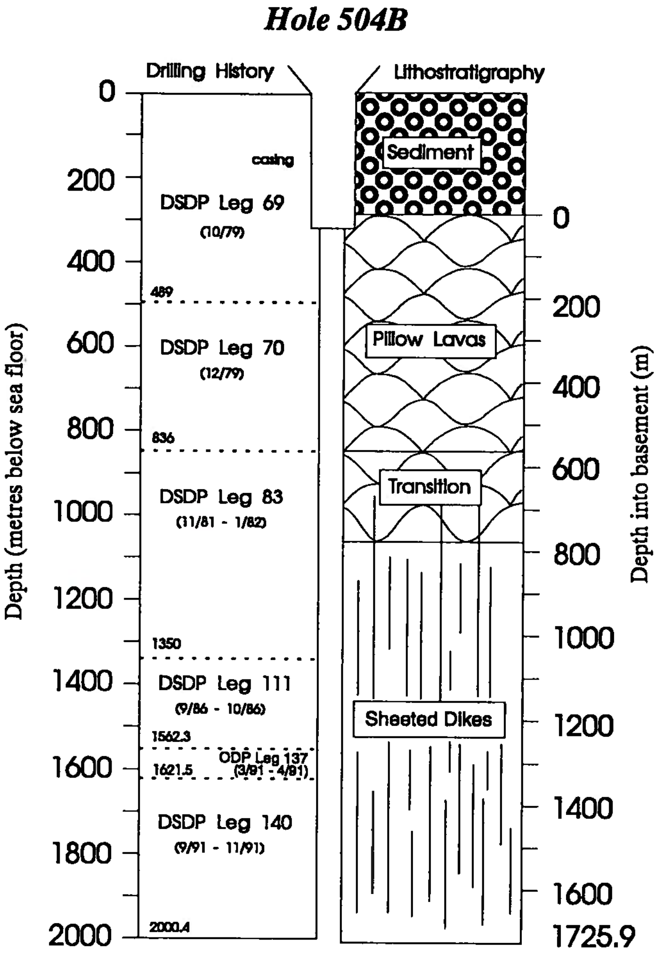


Figure 5. Drilling history and lithologic section of Hole 504B, eastern equatorial Pacific.

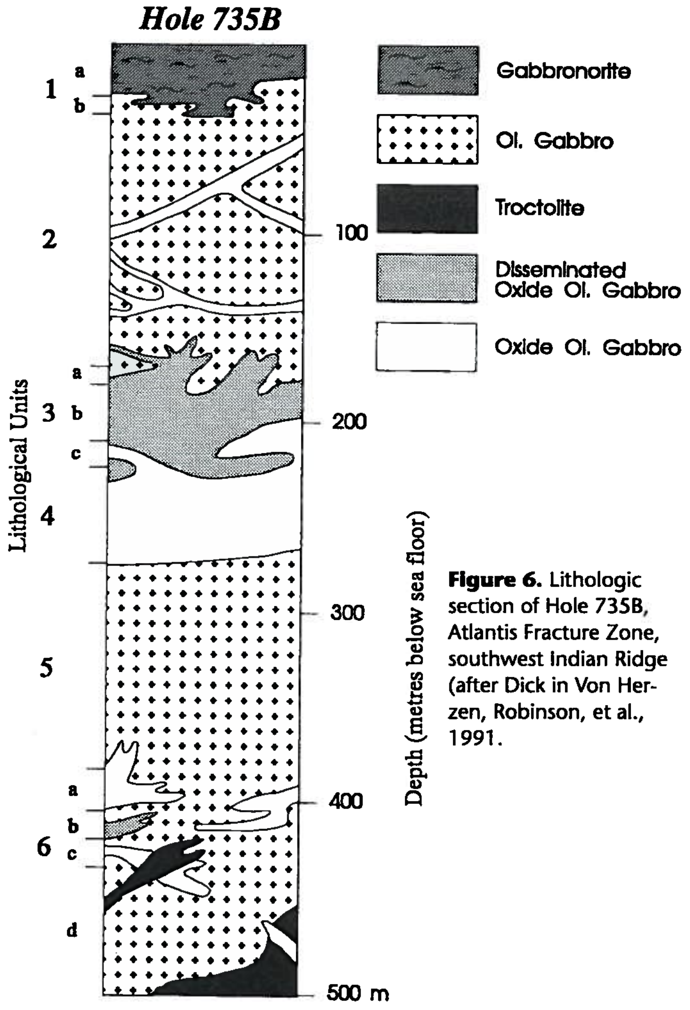


Figure 6. Lithologic section of Hole 735B, Atlantis Fracture Zone, southwest Indian Ridge (after Dick in Von Herzen, Robinson, et al., 1991).

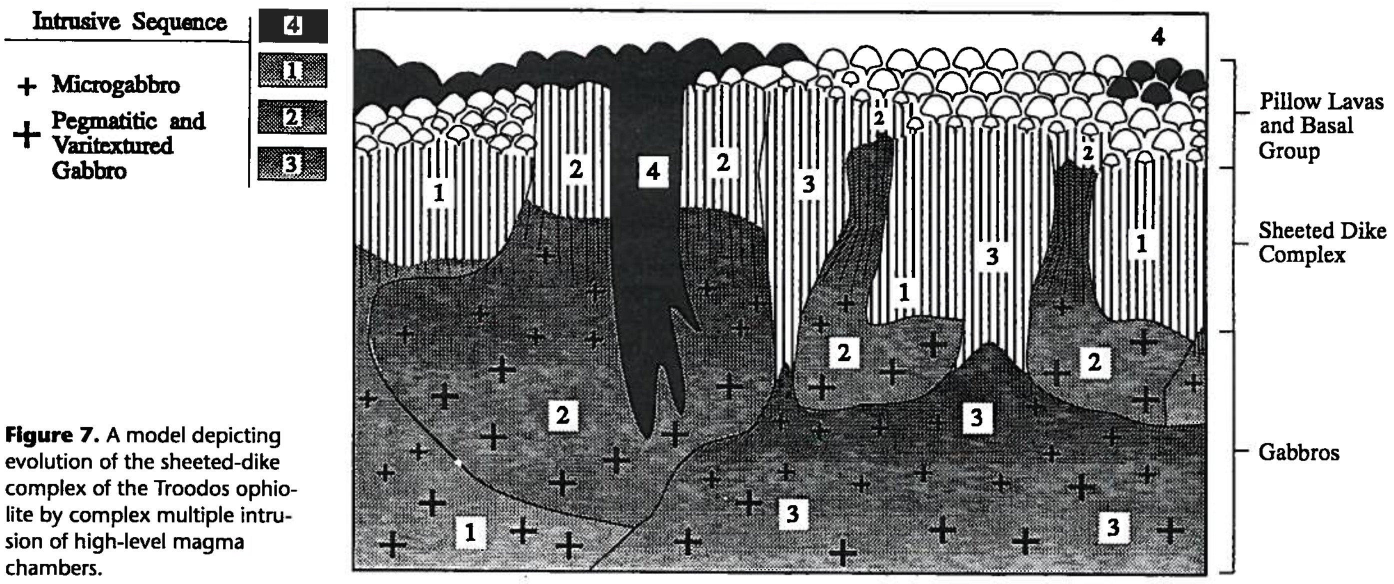


Figure 7. A model depicting evolution of the sheeted-dike complex of the Troodos ophiolite by complex multiple intrusion of high-level magma chambers.

Drilling *continued from p. 55*

If models gleaned from ophiolite studies are compared, it seems as if those that propose small and ephemeral magma chambers are closest to present ocean-ridge reality (Fig. 8). One important feature of these models is that the older parts of the crust undergo high-temperature deformation during lateral translation. This explains the observations that many ophiolitic—and indeed oceanic—gabbros tend to be strongly deformed. Clearly, the deformation process initially takes effect while they are still crystal mushes but continues to well below the solidus and results in much of the observed "layering" in these rocks. The deformation process appears linked to the laminar-flow process that deforms the immediately underlying mantle lithologies observed in complete ophiolite sequences.

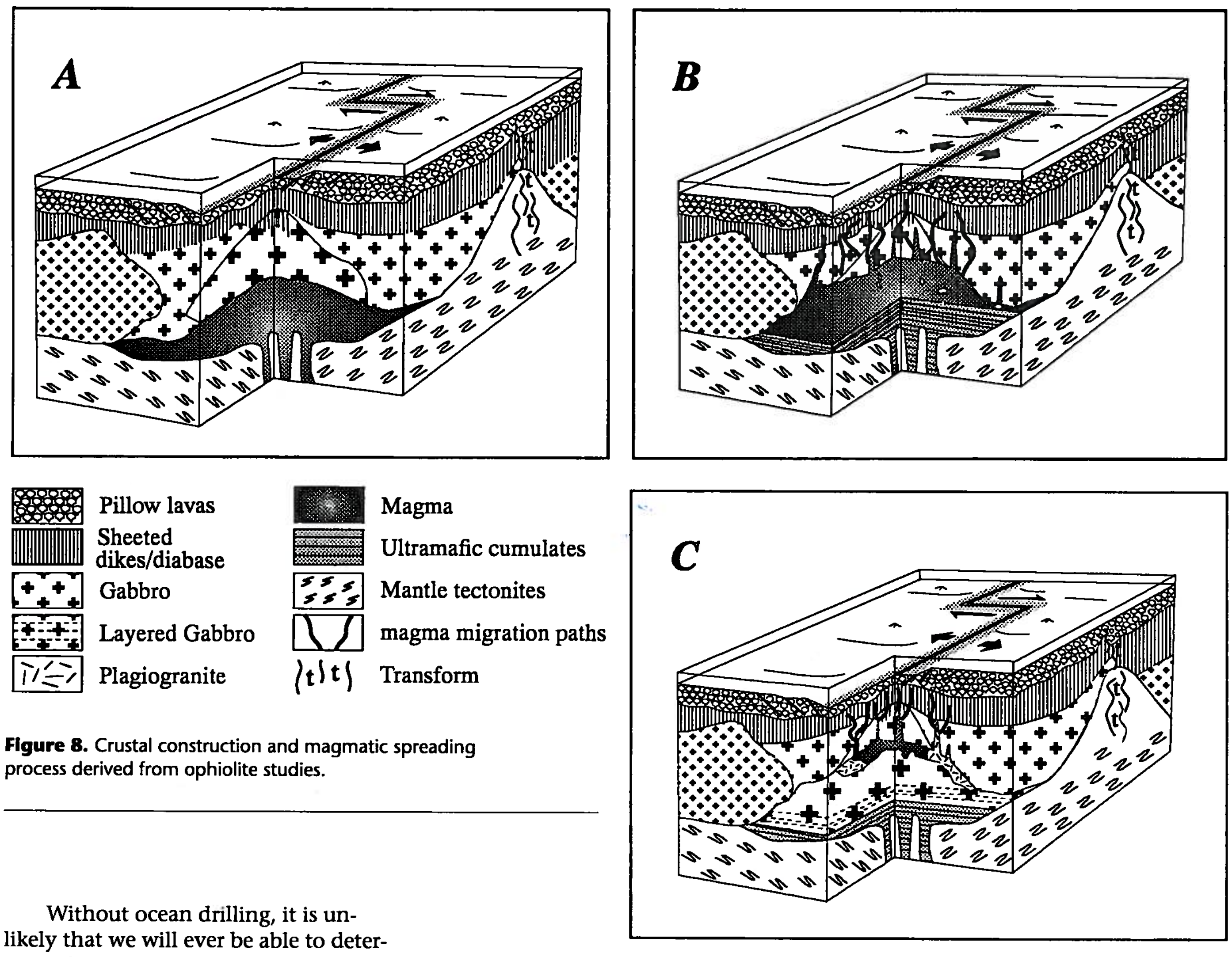


Figure 8. Crustal construction and magmatic spreading process derived from ophiolite studies.

WHY DRILL OCEANIC CRUST AND UPPER MANTLE?

Although the ophiolite analogy has been successful in giving us a first-order picture of the ocean crust and upper mantle, there are problems inherent in carrying it too far. The main one seems to be that, when detailed geology is investigated, there are clearly different models for different ophiolites. Ophiolites also only provide us with ancient sections of the lithosphere that preserve a confusion of sequential processes, including those associated with obduction and postobduction events.

Without ocean drilling, it is unlikely that we will ever be able to determine the average composition of the ocean lithosphere or fully understand the processes that have led to its evolution. So, what is the best way to tackle this problem? A consensus arising from the JOI/USSAC workshop "Drilling the Oceanic Lower Crust and Mantle" (Dick, 1989) describes the following strategy encompassing both long-term and short-term objectives:

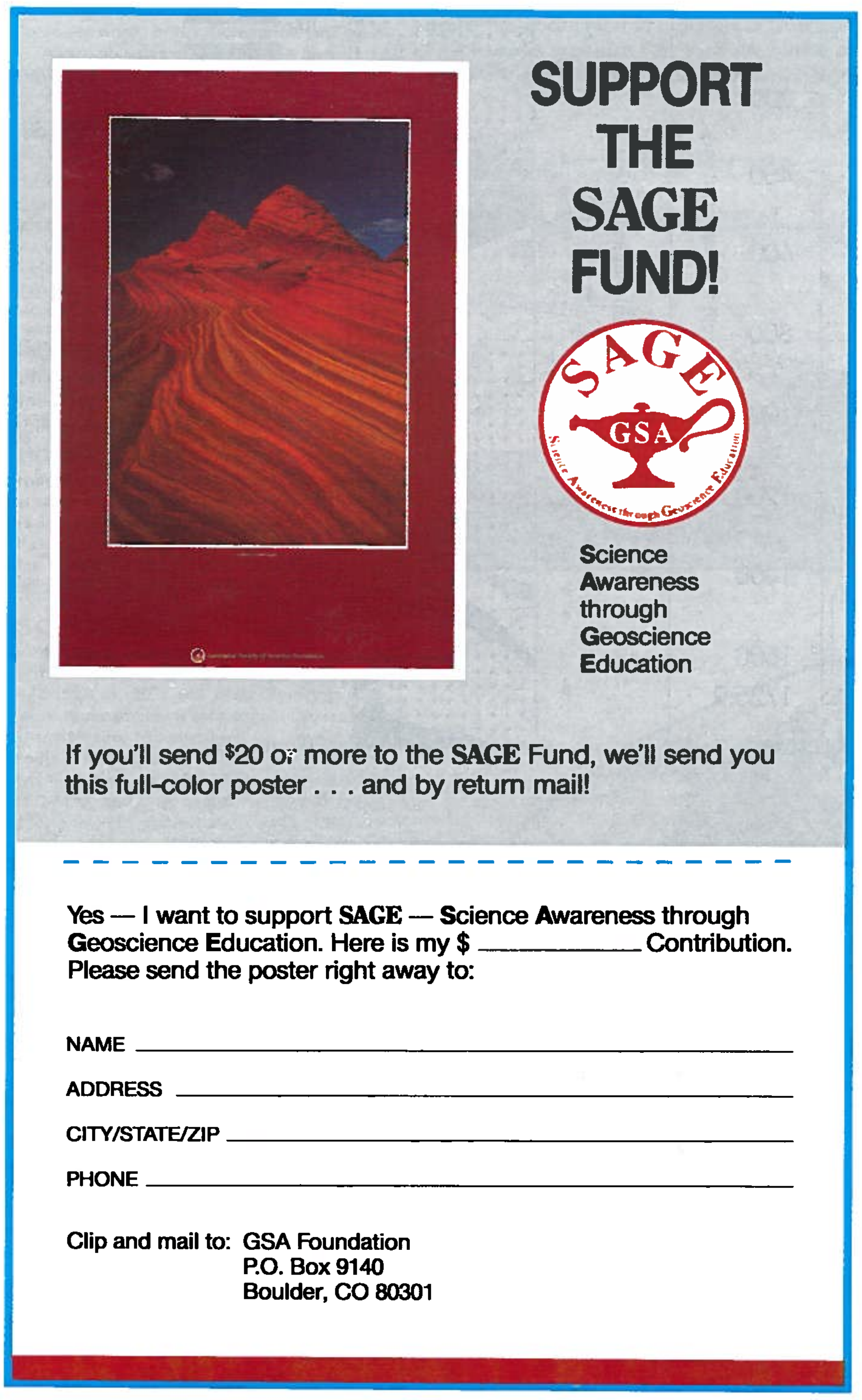
1. Progress should be made on drilling a complete crustal section, to the layer 2-3 boundary in the first instance.
2. A drilling priority is to penetrate the transition zones between oceanic layers—most particularly, the Moho.
3. Obtaining long, uninterrupted sections of the plutonic part of the oceanic crust is of paramount importance.
4. Attempts should be made to core a deep hole in the upper mantle.

The short-term objective is to drill as far as the layer 2-3 boundary, and this appears well within reach in Hole 504B, perhaps on ODP Leg 148. Eventually it will be necessary to drill total crustal sections in order to compare crustal structure with seismically defined layers, to determine bulk (altered) compositions, and to infer the composition of unaltered oceanic crust. In the near future, through programs of offset drilling of those parts of the deep ocean crust that are now found close to or exposed on the sea floor, more data will be made available. This drilling of offset partial sections is a strategy similar to that employed by the Cyprus Crustal Study Project to sample the complete stratigraphy of the Troodos ophiolite through a series of drill holes rather than through one deep and extremely expensive penetration. It was employed during Leg 147 at Hess Deep in the equatorial Pacific in late 1992.

At Hess Deep, East Pacific Rise lower crust generated about 1.2 Ma has been exposed by the westward propagation of the Costa Rica Rift. A long-term program will sample a crustal section from the lavas down to shallow mantle produced at the fast-spreading ridge by drilling a series of holes within the various tectonic blocks that expose different crustal and mantle levels. A major target, drilling through the layer 3–mantle boundary, the petrologic Moho, has been one of the longest sought after objectives of deep-sea drilling, and a major aim of the lithosphere community, who wish to characterize the nature of the Mohorovičić discontinuity and to determine the petrologic and structural transition from crust to underlying residual mantle. During Leg 147, this horizon was penetrated in a series of holes that recovered dunites, harzburgites, troctolites, and gabbros. This drilling emphasized the fact that any successful attempt to address the dynamics of crust-mantle relations requires the recovery of oriented, continuous core to establish a kinematic framework. The definition of meso- and microscale structures in these rocks will aid in the understanding of the rheological laws that operate at these depths. Measurement of other physical properties, particularly those that produce acoustic impedance, is also a priority, but it will have to be made at pressures equivalent to their place of origin—i.e., in properly equipped high-pressure laboratories.

Another long-term objective is to understand the interaction of fluids and rock in, and close to, areas of crustal accretion. Seawater clearly circulates within the upper parts of the oceanic crust, and ophiolites indicate the likelihood of considerably deeper circulation. The emplacement of magma as a heat source beneath spreading centers provides potential for fluid flow and chemical reaction; indeed, the distribution and interaction of fluid and magma must control the cooling surface of magma chambers. In addition, the vigor of circulation affects the size and depth of magma emplacement. Seawater is modified by continuous reaction with ocean crust, circulates through regions of differing physical and chemical potential, and precipitates secondary minerals in cracks and fractures. This affects the circulation patterns as permeability is reduced and results in a complex interdependency of magmatic and fluid-flow processes.

Although the analysis of vent fluids at active hydrothermal sites has elucidated much of the impact of these processes on the character of the shallow ocean crust, much less is known about high-temperature fluid-rock interactions in the deeper crust and upper mantle, particularly at the actual



Penrose Conference Scheduled

From the Inside and the Outside: Interdisciplinary Perspectives on the History of the Earth Sciences

San Diego, March 19–21, 1994

The goal of this conference is to bring together people who write on the history of the earth sciences to discuss key methodological issues arising out of the different approaches taken in this field. A basic premise of the conference is that a deep schism separates the "insider" and "outsider" perspectives in the history of the earth sciences. The scientist-historian finds it difficult to comprehend how anyone who is not an earth scientist can grasp the history of the discipline without mastering it, or understand the internal dynamics of earth science research without taking part in it. Conversely, the historian of science is inclined to believe that scientists lack an appropriately historical outlook and have not learned how to frame historical questions or use historical materials. Scholars in other fields (e.g., sociology, philosophy) are also critical of earth scientists' efforts at humanistic interpretation of their own discipline.

Although there is some recognition of basic common interests between "insiders" and "outsiders," most observers realize that these constitute two rather distinct communities. The earth scientist–historians write primarily for other scientists, using the language and analytical forms of the sciences, and prefer to publish in scientific journals. Historians, sociologists, and philosophers use assumptions, methods, and terminology that may be unfamiliar to scientists, and they usually publish in their own professional journals. These divisions, while perhaps unavoidable, are currently deeper in the writing of history of the earth sciences than in the writing of the history of physics or of biology. This "insider-outsider" dichotomy is ironic, given that one of the primary purposes of historical investigation is precisely to bridge this gap. One authoritative restatement of this purpose, the National Academy of Sciences publication "On Being a Scientist" (1989), called for renewed attention to historical examination of science as a way of integrating social and personal values with the scientific process.

This Penrose Conference aims to assemble "insiders" and "outsiders" for robust and candid exchange on central issues in advancing historical understanding of the earth sciences. Emphasis will be on such issues as the purposes, methods, and analytical processes of research and presentation in the history of the earth sciences, with participants from both sides gaining insight and appreciation of viewpoints other than their own. Prospective participants should include, of course, not only persons already engaged in research in the history of the earth sciences, but also others thinking of entering the field. Thus, graduate students and persons with recent Ph.D.s in the earth sciences or in history, sociology, philosophy, or other disciplines are particularly invited to apply (some financial support may be available to defray expenses). If you would like to attend, please contact one of the co-conveners and indicate your particular area of interest in the history of the earth sciences. If you have relevant work in progress, please briefly state its nature and scope.

Application Deadline:
November 1, 1993.

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margins of magma bodies. One highly visible and challenging target to drill is the "cracking front" that presumably immediately surrounds an advancing magma body. Only by drilling in-situ crust at the spreading axis can the important processes that occur at this interface be investigated while they operate. Ophiolites don't help us here!

THE TECHNOLOGICAL CHALLENGE

Deep-sea drilling has proven to date to be a most successful combination of science and engineering disciplines. In planning a science program involving deep-crustal drilling, it is clear that there must be concomitant engineering developments. If full crustal penetration to the mantle is to be achieved, a drill string at least 11.5 km long will be required. The drill string now on the *JOIDES Resolution* is only long enough to reach layer 3 in comparatively young crust, but not much more. In addition, although the diamond coring system under development is unlikely to aid significantly in the drilling of holes to the mantle, it will be of inestimable value in drilling young, fractured and unconsolidated volcanic rocks at ridge crests. We know from our experience at Hole 735B that conventional rotary coring is very effective in older layer 3 gabbros. Thus, it seems likely that a targeted hole to the mantle is best sited in older and altered crust where the available technology needs the least modification to be successful. Lengthening of the core-retrieval wire will be necessary, and reentry cones will have to be sturdy enough to withstand up to 100 reentries. However, these are not major modifications to equipment, in light of the scientific objectives and potential results. The major concern is the time that will be required to accomplish such drilling and how it might be accommodated into a global drilling program; for example, it is estimated that approximately seven 60-day legs would be required to successfully drill one rotary-cored hole to mantle—more than one year of drilling (Natland et al., 1989). It is in this light that the geological community must ask, Will such a hole be worth it scientifically? Of course, the answer must be weighed against other lithosphere targets for the future. Although the offset partial section strategy provides a means of directly coring plutonic and ultramafic rocks and providing information as to their drillability as well as immediate geologic and geophysical data, to date there has been a clear message from the lithosphere community that the concept of full crustal penetration should be pursued as a long-term objective and that engineering development to allow such drilling must be supported. The immensity of the task may necessitate drilling under different conditions than now exist in the Ocean Drilling Program—i.e., with a fully dedicated alternate platform to the *Resolution*, but there can be no doubt that the potential results from this deep lithosphere drilling will prove a major landmark in our understanding of Earth systems.

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Manuscript received September 7, 1992; revision received December 7, 1992; accepted December 12, 1992 ■

Planning Conferences/Workshops for the Margins Research Initiative

sponsored by
National Science Foundation, Washington, DC

Margin Sedimentation and the Stratigraphic Record
May 2–4, 1993

Thompson Conference Center
University of Texas at Austin

Convenor
ROGER FLOOD
SUNY Stony Brook, Stony Brook, NY 11794
Phone (516) 632-6971

Magmatism and Mass Fluxes at Margins
May 9–11, 1993

Thompson Conference Center
University of Texas at Austin

Convenor
BILL LEEMAN
Rice University, Houston, TX 77251
Phone (713) 527-4892

The purpose of the Conferences/Workshops is to bring together scientists from a wide range of disciplines to discuss research progress in their fields as they relate to problems associated with the *initiation, evolution and destruction of continental margins.*

These meetings will also provide a forum in which researchers can assess future directions for research on continental margins and identify critical areas where development is needed.

Limited travel funds are available to support attendance. Those wishing to attend should send letters of interest **by March 12, 1993** to John C. Mutter, Chairman, Margins Steering Committee, Lamont-Doherty Earth Observatory, Palisades, NY 10964, Attention: Hilary Jones (or Internet: jcm@lamont.ldgo.edu or hilary@lamont.ldgo.edu).

Correction:

The phone number for the Geological Society of London was incorrectly published on the ad appearing in the January issue of *GSA Today*. The correct number is (0225) 445046. We regret any inconvenience this error may have caused.