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Future Scientific Drilling of Oceanic Crust

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Processes that occur within and across the oceanic crust—in particular along mid-ocean ridges and oceanic spreading centers—play a huge role in the dynamics of the Earth. The largest fluxes of heat and material between the Earth's mantle, crust, and seawater occur via magmatic, tectonic, and hydrothermal processes along oceanic spreading centers and their vast flanks. Roughly two thirds of the Earth's surface is accreted through magmatic and tectonic processes along mid-ocean ridges, and subduction of this ocean crust in turn influences mantle compositions. Exchange of elements between ocean crust and seawater strongly influences seawater compositions and leaves a geologic record of fluid-rock reactions in altered ocean crust. Some of these reactions contribute energy to microbial activity of a largely unexplored biosphere. The dynamics of ridge and ocean crustal processes therefore have enormous implications for thermal, chemical, and biological exchanges between the solid Earth and the hydrosphere.

Fully understanding these processes will require scientific drilling. Drilling and retrieving cores allows researchers to get a snapshot of crustal properties through time at specific locations. Examining differences between cores across the ocean could further help researchers form a basic picture of the processes that govern ocean crustal processes. The current stock of retrieved cores and data from borehole logging and experiments offers tantalizing glimpses of several processes, including how crust is generated, or accreted, at mid-ocean ridges, how oceanic crust is a significant sink for important chemical constituents of seawater (including carbon in some instances), how microbial communities are able to live deep within ocean crust, how seawater-crust exchanges may have changed over geologic time with varying climactic conditions, and how pathways of heat and chemicals move between the solid Earth, oceans, and biosphere (see Figure 1). But to further quantify these processes, new drilling and a broader drilling strategy are required that take advantage of the latest drilling and downhole sampling (of both fluids and rocks), experimentation, and logging technology.

Primary themes of future scientific investigation can be divided roughly into three groups: (1) accretion of ocean crust, especially active geologic, geotectonic, and biological processes surrounding the ridge axis (the axial zone); (2) hydrological-geochemical-microbiological feedbacks as ocean crust matures and migrates from spreading centers; and (3) lithospheric heterogeneity and corresponding biological diversity in slow and ultraslow spreading crust. Interdisciplinary approaches and projects are needed to address these major themes, which will bring exciting new challenges and opportunities during the next phase of ocean drilling.

Accretion and Axial Zone Processes

Oceanic crust is accreted and rapidly evolves during the first few million years of seafloor spreading through vigorous volcanic, hydrothermal, and deformational processes within the axial zone. Thus, understanding axial zone dynamics is very important to our understanding of how crust is sustained and recycled on Earth.

Because little sediment has accumulated and only a thin crustal layer separates the oceans from the mantle, young oceanic crust surrounding the ridge axis also

Fig. 1. In March–April 1991, divers aboard Alvin *observed an astounding bloom of chemosynthetic microbes during an eruption of the East Pacific Rise crest around 9°N. In this photo, fragments of white microbial sulfur floc are being blasted out of the seafloor by hot water venting from the volcanic fissure that fed the eruption. The sulfur floc was precipitated on and under the seafloor by microbial oxidization of hydrogen sulfide. This phenomenon suggests the possible existence of an extensive subsurface biosphere fueled by chemical energy and illustrates the very active exchange processes that take place at mid-ocean ridges [*Haymon et al., *1993]. Oceanic drilling in such harsh environments could reveal a wealth of new information about these vital areas.*

By N. W. Hayman, W. Bach, D. Blackman, G. L. Christeson, K. Edwards, R. Haymon, B. Ildefonse, M. Schulte, D. Teagle, and S. White

plays direct and critical roles in the thermal, chemical, and biological exchanges between the hydrosphere and solid Earth. Magma distribution; crustal cracking; the depth, vigor, and geometry of hydrothermal circulation; and subseafloor biological activity are inexorably linked to one another. Understanding and quantifying these processes and their linkages will permit quantitative estimates on the biological productivity of the axial subseafloor biosphere, helping to answer questions such as, What is the magnitude of processes in the subsurface compared with biological expression at the seafloor? What are the major metabolic pathways and biogeochemical consequences of these activities in the Earth system?

Progress on many of these issues is restricted by a dearth of information on ocean crustal permeability. Are fluid pathways dominated by faults, fractures, or the permeability of undeformed rocks? How does permeability and fluid flow vary with depth, time, and crustal age, particularly along and across ridge axes? Few constraints are known on the residence time for hydrothermal fluids and how microbiological activity varies within a hydrothermal system. For example, it is debated whether fluid flow is required to transport nutrients to subseafloor microbial communities in ocean crust of all ages. Carbon cycling in ocean crust, and its role in the global carbon cycle, is also unknown. Some scientists suggest that subseafloor pathways allow the dispersal of biota, but this hypothesis remains untested. Moreover, are temperature and availability of chemical energy sources and/or other nutrients the limiting factor for the subsurface biosphere? And what are the influences, or feedbacks, of biological processes on the hydrologic properties of the oceanic crust?

The transport of magma from the mantle and its cooling and crystallization within and atop the mid-ocean ridge axial zone are the primary mechanisms that build the ocean crust and drive hydrothermal circulation. Most of this magma crystallizes to form gabbroic rocks in the lower ocean crust, but researchers lack direct constraints on magma distributions and rates of cooling and crystallization. For example, whether there is significant chemical partitioning between the upper and lower crust and whether there is significant off-axis magmatic addition to the lower crust remain unknown. Competing models for ocean crustal accretion can be assessed further only through the study of genetically related mantle, lower crustal, and extrusive sections.

It is no surprise therefore that drilling a complete ocean crustal section into in situ mantle has been, and remains, a long-term priority goal of scientific ocean drilling. Such deep drilling will also ground truth seismic data and finally establish whether the seismic *Mohorovičić* discontinuity (Moho) is a fundamental petrologic boundary in the Earth's interior.

Maturation Processes

Though there are many unanswered questions about crustal accretion and hydrothermal systems within spreading centers, there are arguably even fewer constraints on the maturation of oceanic lithosphere on ridge flanks. Seawater-crust exchanges during maturation affect ocean crustal composition, permeability, and geophysical properties and are a major influence on seawater chemistry. Secondary minerals from fluid-rock reactions may provide a largely unrecognized record of past seawater compositions and a possible record of global environmental change. Crustal aging likely affects the microbial biogeography of the seafloor and subseafloor biosphere, but how microbial biomes—taxonomically and functionally—vary spatially and temporally in ocean crust remains unknown. Moreover, as scientists get a better understanding of the in situ physical properties of the ocean crust of different ages, they will be able to improve the use of geophysical data such as velocity and magnetization to gain regional perspectives on crustal aging.

A widely articulated vision by workers in the field is to conduct drilling transects that specifically "track" the aging of the crust along ridge flank segments. Through such an effort, scientists can determine the integrated effects over time of chemical, thermal, and biological processes and exchanges between the oceans and crust. Transects would aim at elucidating the interrelationships among ocean chemistry, ocean sedimentation, crustal evolution over geological time, and global biogeochemical cycles. Conspicuous gaps in sampling include crust younger than 3 million and 45–80 million years old, the latter interval coinciding with an area of the seafloor where, on average, no anomaly in conductive heat loss is observed. Absence of a heat flow anomaly suggests that older crust is sealed to hydrothermal circulation. However, global data averaging filters out important local effects, and hydrothermal circulation is expected in crust of all ages wherever hydrologic head exists.

Lithospheric Heterogeneity

It is now recognized that exhumed mantle and lower crustal rocks dominate at least 25% of the slow and ultraslow spreading (full spreading rates of approximately <55 and <20 millimeters per year, respectively) ocean ridge systems. The interplay of faulting, hydrothermal alteration, and magmatism in these settings is only now being intensely scrutinized, and new observations are challenging older notions of crustal accretion processes.

For example, workers are still evaluating the differences between crust formed predominantly through faulting and that formed predominantly through magmatism. Where mantle rocks are exhumed during faulting, serpentinization occurs, changing the composition and mechanics of the crust as water is trapped in hydrous minerals. In places this can cause carbonate veining that can lead to extensive and complex hydrothermal vent sites and may create a significant carbon sink. Serpentinite-hosted hydrothermal systems exhibit distinctive fluid chemistry and fauna, and these systems contrast with basalt-hosted hydrothermal systems. Biological exchanges that thrive via serpentinization reactions may have early Earth and extraterrestrial analogues with implications for origins of life. Yet even the most basic questions about this process remain unanswered: Does serpentinization influence the nature and diversity of some deep-sea ecosystems? What is the extent and distribution of serpentinization at depths greater than the top 100 meters and two deep (>1 kilometer) sections of slow spreading crust currently explored by drilling? What are the time scales of serpentinization? Is exhumed lithospheric heterogeneity reflected in patterns of microbial diversity and function?

Accessing the Deep Crust

Whether it is drilling axial crust, off-axis crust, or deep holes toward the Moho, the technological challenges of scientific drilling are considerable. Recent work has made several strides toward easing these challenges, and the successful drilling of four deep (>1-kilometer) holes (two in slow spreading crust and two in fast spreading crust) in ocean crust by the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP) brought renewed energy and impetus to scientific drilling of ocean crust.

Technological advances for ultradeep drilling such as those recently explored by ODP and IODP have focused on hole stability, which is greatly improved by using engineering muds instead of seawater for a drilling fluid. Mud operations require either using a riser (currently possible only at water depths less than 2500 meters) to circulate mud back to the ship, or alternatively expelling all mud to the seafloor (expensive for deep drilling as well as environmentally problematic). An exciting development is a joint industry/IODP-funded project to develop a riserless mud recovery system with seafloor-based operation. This will permit using engineering mud at water depths greater than 2500 meters and could be the key to a successful deep hole through oceanic crust.

Recovering Cores From Young Crust

Axial zone drilling also requires that scientists and engineers overcome challenges surrounding hole stability, recovery, and ship motion (heave compensation) while penetrating the tough but friable basaltic crust. Drilling young, fractured basalt has been especially challenging, with no existing holes penetrating more than 200 meters into basement in crust younger than 3 million years old. However, recent lessons from on-land drilling of very young basalts in geothermally active areas in Iceland and Hawaii lead to optimism that the long-sought-after goal of drilling into young ocean basalts can soon be realized.

New drilling technology to overcome the challenge of initiating a hole in young, friable basalt includes the hard rock reentry system (HRRS) and the advanced diamond core barrel (ADCB) system. HRRS simultaneously drills a hole using a hydraulic hammer and runs casing, which reduces the risk of hole collapse that has been observed with conventional reentry systems. HRRS was tested near the Mid-Atlantic Ridge in 2004 and in the Manus basin off Papua New Guinea in 2000. Diamond coring has proven extremely successful in on-land drilling in Iceland and was also used to recover intensely fractured dacite in the Manus basin. Yet even when performing well, each technology has limitations. HRRS makes a hole for the casing without coring; it is a critical tool for hole initiation but must be used in conjunction with other equipment for studies that require sampling the very uppermost basalts of unsedimented ocean crust. In contrast, the primary challenge in using the ADCB system for ocean crust drilling is providing minimal weight-on-bit variation.

Two developments in scientific drilling are promising for drilling young ocean crust. First, the recently refitted passive heave system on the IODP's R/V *JOIDES Resolution* should result in a more stable platform and a higher chance for successful drilling, and the Japanese Agency for Marine-Earth Science and Technology's R/V *Chikyu* provides an even more stable platform. Additionally, a frontier technological area for both scientific and industry drilling is the deployment of remotely operated submersible drill rigs. Several types of submersible drill rigs are rated to ocean depths of 3000–4000 meters and can drill the upper 100–150 meters of the crust with good core recovery.

Drilling as a Common Baseline for Studies of the Oceanic Crust

Although ocean crust presents challenging conditions, technology development is such that successful drilling of the axial zone and the deeper crust is achievable.

But this is only the start. By combining drilling with borehole experiments and in situ borehole observatories (including existing and new sampling capabilities and sensors), scientists can detect and monitor biological activity and active fluid flow in the crust, and characterize chemical fluxes and the evolution of chemical architecture in young crust. Long-term instrument deployments and active experimental Circulation Obviation Retrofit Kit (CORK) observatories are revealing first glimpses of the dynamics of shallow mid-ocean ridge processes on short (instantaneous to decadal) time scales. Observatories are often the only way to monitor in situ ocean crustal conditions, collect valuable specimens, determine physical properties, and calibrate remote geophysical observations. An interesting development is the use of observatories to test hypotheses about crustal properties through manipulative experimentation in real time (e.g., hydrological and biological tracer studies).

Drilling also can be combined with geophysical investigations (seismic, magnetic) of the areas surrounding the cores, allowing researchers to ground truth structures only remotely sensed. Further, in combination with numerical models, scientists can mesh together data from cores with other sources of information to gain a broader picture while also arriving at a deeper understanding of ocean crustal processes.

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Reference

Haymon, R. M., et al. (1993), Volcanic eruption of the mid-ocean ridge along the East Pacific Rise crest at 9°45–52'N: Direct submersible observations of seafloor phenomena associated with an eruption event in April, 1991, *Earth Planet. Sci. Lett., 119*(1-2), 85–101.

Author Information

Nicholas W. Hayman, Institute for Geophysics, University of Texas at Austin; E-mail: hayman@ig.utexas.edu; Wolfgang Bach, Department of Geosciences, University of Bremen, Bremen, Germany; temporarily at Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, Mass.; Donna Blackman, Scripps Institution of Oceanography, University of California, San Diego, La Jolla; Gail L. Christeson, Institute for Geophysics, University of Texas at Austin; Katrina Edwards, Department of Biological Sciences, University of Southern California, Los Angeles; Rachel Haymon, Marine Science Institution, Department of Earth Science, University of California, Santa Barbara; Benoit Ildefonse, Géosciences Montpellier, Université Montpellier 2, CNRS, Montpellier, France; Mitch Schulte, University of Missouri, Columbia; Damon Teagle, School of Ocean and Earth Science, National Oceanography Center, University of Southampton, Southampton, UK; and Scott White, Department of Geological Sciences, University of South Carolina, Columbia