Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings

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Abstract

The global mid-ocean ridge system generates two-thirds of the solid earth surface and produces more than half of the annual volcanic volume erupted on the earth. Active volcanic, hydrothermal, and structural processes mainly transpire within the first few million years of seafloor spreading, on the crest and young flanks of the mid-ocean ridge. In this active zone little sediment has yet accumulated, and only a thin crustal layer separates the oceans from the mantle. This young crust directly mediates extensive thermal, chemical, and biological exchanges between the hydrosphere and solid earth, releasing nearly half of the total oceanic hydrothermal heat flux. Yet the impact of these vast exchanges through young ocean crust remains poorly known, and include inorganic and organic carbon fluxes that may be important to earth's climate and biosphere.

Although it was recognized more than 30 years ago that young ocean crust processes play a major role in the earth system, study of these processes has been impeded by insufficient access to the third dimension. Attempts to drill young ocean crust have been rare, and were stymied in the 1990's by stalled development of necessary drilling technology. Successful IODP drilling into older volcanic basement has greatly influenced mid-ocean ridge studies, but also has underscored the need for in situ measurement and samples from young ocean crust.

New hard rock drilling tools and approaches have been developed by others as well as by IODP. Independent efforts to monitor hydrothermal and volcanic activity and the recent results of extensive seafloor mapping and seismic imaging offer logistical and scientific benefits. With a renewed commitment to engineering, integration of new tools, adequate support for scientists, and a general commitment to ocean crustal drilling, scientists are now poised to test many of the hypotheses in ocean ridge research through drilling of young ocean crust.

Introduction

The Earth's largest fluxes between mantle, crust, and seawater occur on the mid-ocean ridges (MORs), and a largely unexplored biosphere capitalizes on the ridge's unique thermal and chemical conditions (Figure 1). MOR processes therefore continue to be frontier areas of research, and scientific ocean drilling is one of the only ways to access the ocean crust's subsurface.

Figure 1. In March-April, 1991, divers in Alvin witnessed an astounding bloom of chemosynthetic microbes during an eruption of the East Pacific Rise crest at lat. 9º45'-52'N (Haymon et al., 1993). In the 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 is precipitated on and under the seafloor by microbial oxidization of hydrogen sulfide. This dramatic and unexpected sight suggested the possible existence of a vast subsurface biosphere fed by chemical energy, and contributed to a paradigm shift in ideas about how planets give rise to life.

The past decade has seen successes in deep drilling of relatively old ocean crust outside of the volcanically and hydrothermally active spreading centers. These deeper crustal explorations have confirmed the linkages between hydrothermal activity and magmatism, and have extended our view of the magmatic processes in the lower crust and their thermal effects on the upper crust. Along with submersible investigations and sonar mapping, deep crustal drilling has also shown us that the sheeted dike complex and much of the thick volcanic sections of fast-spread ocean crust develop through a combination of subsidence and faulting on/near the ridge crest and from eruptions that flow off-axis to abyssal hills.

In contrast with ocean drilling, seafloor studies of ridge crests and flanks has provided a rich spatial and temporal view of ridge processes. Volcanic units have a much larger range of compositions and flow morphologies than previously thought, hydrothermal cells have been mapped with microseismicity, relatively 'hot' and 'cold' regions of ridges have been mapped with geophysical and geological techniques, and seismic images show a potentially broad region of magmatism extending beneath the axial flanks. Well-documented examples of hydrothermal activity along abyssal hills also point to a broader region of activity extending onto the ridge flank.

The dynamics of ridge processes have enormous implications for both chemical and biological exchanges between the solid earth and the hydrosphere. Firstly, the flux of metals and chemical species between seawater, crust, and mantle strongly influences the composition of the oceans and leads to mineral deposits containing a geologic record of the fluid-rock reactions. Secondly, the temperature and redox gradients set up by the hydrothermal systems promote microbiological activity, and deep-sea organic matter can be sequestered in the crust, or alternatively consumed during biological processes.

Virtually every hypothesis arising from these observational efforts requires further ocean drilling to provide the required tests. The most direct approach is to drill very young ocean crust to overcome the overprinted ambiguity of the geologic record, and to understand mechanisms in the subsurface that lead to the activity observed on the seafloor. The reward for such a renewed commitment to drilling young crust will be breakthrough science. With the next phase of drilling, we can do much to: characterize the initial inhabitants of the subseafloor biosphere, and establish the spatial extent and physiological limits to subseafloor life; elucidate active processes of crustal creation pervasively influencing the properties of all oceanic basement; identify and quantify the large fluxes between the oceans and young ocean lithosphere, including those affecting carbon cycling; ascertain the initial conditions of ocean crust, and explore the evolution of ocean crust properties, fluxes, and subseafloor biosphere as the seafloor ages.

Hypotheses Potentially Testable By Drilling Young Ocean Crust

To convey the richness of ocean ridge science that can be addressed by drilling young crust, a list of key hypotheses was compiled during a COL-Sponsored workshop on Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings held August 27-28, 2009 in Austin, Texas. Some of these hypotheses are not new, but endure because they are critical and require bold new approaches to test them. Other pioneering hypotheses have arisen recently from new data and investigative approaches.

The hypotheses are grouped into two families: “physical properties of the oceanic crust”, and “active processes along mid-ocean ridges”. The former emphasizes the maturation of the crust during initial spreading from the axis to the flanks, and focuses on data that can be attained from core combined with geophysical data. The latter emphasizes hydrothermal and biological processes, and focuses on data that are derived from a broader suite of down-hole data, which in some cases do not require core acquisition.

Physical Properties of Oceanic Crust

- The seismic velocity of the crust – one of our best sources of regional data from the ocean crust’s subsurface – is controlled either by igneous lithology or by secondary alteration.
- The first-order decrease in magnetization with distance from ridge axes is controlled either by alteration, or by changes in the Earth's magnetic field.
- Volcanic construction of the crust occurs across a narrow area at the ridge axis, or alternatively off-axis volcanism is an important contributor.
- Brittle deformation of the upper crust, which provides subseafloor fluid pathways and accommodates strain, occurs primarily syn-magmatically near the ridge axis, or alternatively along major abyssal hill-forming faults.
- Mass flux of chemical species and metals between the oceans and crust –a major buffer for seawater composition - is determined by fluid-rock reactions at the ridge axis, or alternatively develops slowly as crust matures.
- Magmatic volatiles are a source of mass flux into the oceans, or alternatively all mass flux is due to water-rock reactions.
- Changes in the composition of lava flows occur on short (e.g. 1000 year) time scales or alternatively reflect a longer process.
- Magmatic processes in the lower crust are a major contributor to the diversity of compositions in the upper crust, or alternatively crustal compositions are a direct

consequence of mantle melting.

- The lower crust is built by stacking of gabbro sills, or alternatively is built by large-scale solid-state flow from thin magma lenses.
- Hydrothermal systems have an alteration halo that have an aspect ratio of 1, or alternatively physical properties of the crust and dynamics of fluid flow cause anisotropy in the hydrothermal system.
- Hydrothermal deposits persists through time, or alternatively they are ephemeral and in many instances not well preserved.

Active Processes at Mid-Ocean Ridges

- An along-axis hydrothermal convection cell has been identified on the East Pacific Rise (near 9° 50' N) using microseismicity data and it is predicted that the residence time for fluid within this cell is on the order of nine months.
- Along-axis redox and temperature gradients that promote microbiological activity exist along strike in ridge-parallel hydrothermal cells and around zones of recharge and discharge.
- Deep sea organic matter is incorporated into basaltic crust during hydrothermal recharge, where it is either sequestered, transformed, transported or available for microbiological processes. Organic compounds are made both biologically and abiotically in crustal fluids.
- Seawater entrainment into high temperature discharge zones causes anhydrite precipitation in voids and other pore space, reducing porosity and permeability. The anhydrite may be replaced by quartz resulting in more permanent permeability reduction.
- Seawater entrainment into downwelling recharge areas and into high temperature discharge zones creates redox and thermal gradients that affect many processes, including water-rock reactions and microbiological metabolisms. These are local phenomena that can be constrained spatially by drilling.
- There are subseafloor pathways for dispersal of biota.
- Brines from hydrothermal phase separation are stored in the subsurface crust for unknown periods of time, affecting physical properties of the crust and ore deposition, and potentially serving as habitats for halophilic microorganisms.
- Precipitation of carbonates occurs during seawater-rock reactions, and may be of sufficient magnitude to affect global carbon cycles.
- Pressure perturbations are important drivers of hydrothermal flow both on and off axis.
- The microbiology that has been sampled to date on the seafloor at hydrothermal vents represents only a small fraction of the microbial diversity that exists within the subseafloor crust.
- The limit to the temperature at which a subseafloor biosphere can exist is >125ºC.
- Gradients in the seafloor created by permeability contrasts and fluid flow provide habitats for life in the subseafloor crust.
- Availability of chemical energy sources and/or other nutrients may be the limiting factor for the subsurface biosphere rather than temperature.
- Consumption of basaltic glass by microorganisms is a response to the cessation of fluid flow and resulting dearth of dissolved chemical substrates for chemolithoautotrophy.
- There are active magmatic and hydrothermal processes associated with off axis sill intrusions, and these processes may be common in young crust on ridge flanks.
- Abyssal hill hydrothermal systems along young ridge flank fault scarps may tap heat from either axial and/or off axis melt sills, and be frequently rejuvenated by fault movements and/or earthquake pressure pulses.

- Fluid, chemical, and thermal fluxes on off-axis faults are triggered by earthquakes in the active plate boundary zone, and persist long enough to be significant in magnitude.

Technological Advances

Historically, drilling and coring young oceanic crust has been extremely challenging; no existing holes penetrate more than 200 m of basement in <3 Ma crust. However, on-land drilling in Iceland and Hawaii prove that deep holes in young basalts can be realized, and new ocean drilling technologies are now available that provide optimism that successful drilling of young mid-ocean crust can now be achieved.

Initiating a hole in young basalts with little sediment cover has proven particularly difficult. The hard rock reentry system (HRRS) provides a technological solution with the ability to install casing with reentry capability on a sloping or rough hard rock seafloor. The system simultaneously drills a hole using a hydraulic hammer and runs casing, which reduces problems due to hole collapse that have been observed with conventional reentry systems. The HRRS has been successfully deployed on the Atlantis Massif and the Manus Basin. Although the HRRS should provide the hole initiation that has hindered previous drilling efforts, one limitation is that there is no core recovery in the cased interval. Newly developed remotely-operated submersible drill rigs can fill in this gap. Several types of submersible drill rigs are rated to depths of 3000-4000 m, and can drill the upper 100-150 m with good core recovery. Seafloor drills might be used for site survey purposes, with subsequent deeper drilling using the HRRS as a means to start a hole before continuing with the more robust IODP coring tools.

Core recovery of basalts using traditional coring systems has been poor, but the advanced diamond core barrel (ADCB) coring system provides an alternate technique for recovery in these fractured formations. Diamond coring has proven extremely successful in on-land drilling in Iceland, and has been used during ODP Leg 193 to recover intensely fractured dacite in the Manus Basin. The primary challenge with using the ADCB system for ocean crust drilling is that it requires minimal weight on bit variation; however, the refitted passive heave system on the JOIDES Resolution should result in a more stable platform and a higher chance for successful drilling. Testing is presently underway with the refitted passive heave compensator.

A frontier area for ocean crustal sciences is to directly access the relatively high temperature (e.g. >200°C) rocks and fluids beneath the ridge system. Aside from direct sampling, borehole experiments and in situ borehole observatories (including existing and new sampling capabilities and sensors) are needed to detect and monitor biological activity and active fluid flow in the crust, and to characterize chemical fluxes and the evolution of chemical architecture in young crust. In some cases this may require a paradigm shift away from a focus on core recovery, and toward an emphasis on borehole installation.

Investigative Approach

In order to maximize scientific results, drilling of young ocean crust can build on other major investments and discoveries. Three strategies for drilling young ocean crust can immediately be identified, though these are not all-inclusive. First, a transect of drill holes from ridge crest to several kilometers out on the ridge flank would directly confront the initial aging of the crust. Understanding the initial stages of crustal evolution is critical because this is the area where conductive heat flow drops precipitously, magmatic and volcanic construction occur, and active faulting and most of the conspicuous hydrothermal alteration takes place. One well-designed drilling transect could test many of the hypotheses described above.

Second, a drilling program could take advantage of seismological, hydrothermal, and magnetic studies that constrain a more detailed picture of ridge hydrothermal and subseafloor microbial processes, wherein relatively hot and cold zones form along a ridge axis. By targeting the different thermal environments, drilling could access materials and organisms from different parts of the magmatic-hydrothermal system, thereby addressing hypotheses about the dynamics of axial fluid flow.

Third, targeting one key area such as a young abyssal hill or a seamount could address the breadth of the axial region's magmatic and hydrothermal system, determine the importance of faulting and deformation in the near-axis ridge flank region, and illuminate the diversity of and controls on the subseafloor biosphere.

Summary Statement

It is recognized that the MOR environment presents challenging conditions for drilling, but technology has developed such that successful drilling in this environment should now be achievable. However, it is imperative that technology development continue in any future ocean drilling program, and that time for engineering tests become part of all drilling legs. Rapport between scientists and engineers also should be fostered; scientists need to know what is feasible in order to develop the science and engineers and managers must know what is desired by the scientific community to develop better tools and approaches. Science must lead the way, however, including embracing alternative drilling platforms, and encouraging communication between continental and ocean drilling communities, and programs focused on monitoring and seafloor observational efforts. Also required is adequate support for scientists to insure generational continuity in this long-term effort. MORs are the crucible in which much of the earth's lithosphere is forged, and are the keystones of Earth's planetary processes. Only by drilling can we probe and systematically sample the active third dimension of this vast and globally significant system.

Reference:

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