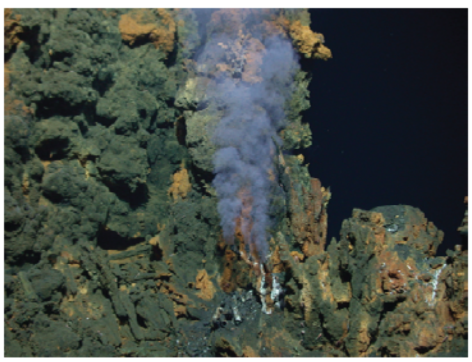
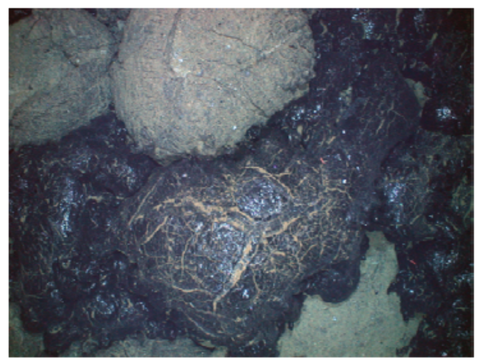
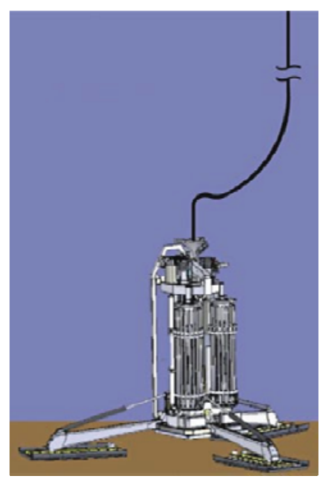
Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings

A Workshop Sponsored by the Consortium for Ocean Leadership and the Jackson School of Geosciences, University of Texas at Austin







Austin, Texas
27-28 August 2009

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

Workshop Sponsors

Consortium for Ocean Leadership
Jackson School of Geosciences, University of Texas at Austin

Conveners

Gail Christeson[1], Nicholas W. Hayman[2], Rachel Haymon[3], Mitch Schulte[4], Scott White[5]

[1]The University of Texas at Austin Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, J.J. Pickle Research Campus, Bldg. 196 (ROC), 10100 Burnet Rd. (R2200), Austin, TX 78758-4445, U.S.A., email: gail@ig.utexas.edu.

[2]The University of Texas at Austin Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, J.J. Pickle Research Campus, Bldg. 196 (ROC), 10100 Burnet Rd. (R2200), Austin, TX 78758-4445, U.S.A., email: hayman@ig.utexas.edu.

[3]Department of Earth Science, 1006 Webb Hall – MC 9630, University of California, Santa Barbara, CA 93106-9630, email: haymon@geol.ucsb.edu

[4]Department of Geological Sciences, 101 Geology Building, University of Missouri, Columbia, MO 65211, email: schultemd@missouri.edu

[5]Department of Earth and Ocean Sciences, 701 Sumter St., EWS 617, University of South Carolina, Columbia, SC 29208

Table of Contents

Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings....................................1

Summary....................................4

Introduction....................................4

Scientific Motivation....................................7

Accretion of ocean crust and properties of the axial lithosphere....................................7

Aging of ocean crust along axial flanks....................................10

Hydrothermal Processes....................................11

Ocean crust ecology....................................12

Technology: Challenges and Solutions....................................13

Presentation: Jay Miller, ‘Historical Developments in Scientific Drilling on and About Mid-Ocean Ridges’....................................13

Presentation: Leon Holloway, ‘Seafloor Drills’....................................17

Presentation: Greg Myers, ‘Engineering to Support Transformative Science’....................................18

Summary of Technological Advances and Engineering Challenges....................................20

Breakout Group: Physical Properties of Oceanic Crust....................................21

Hypotheses: Physical Properties of Oceanic Crust....................................21

Potential Drilling Program: Transect of Multiple Holes on a Flowline....................................22

Potential Drilling Program: Target upflow and downflow crust along and across axis....................................22

Potential Drilling Program: How does observed spatial variability at the seafloor relate to deeper processes?....................................23

Breakout Group: Active Processes at Mid-Ocean Ridges....................................23

Hypotheses: Active Processes at Mid-Ocean Ridges....................................23

Supporting the Science and the Scientists....................................25

Engineering support and scientific input....................................25

Scientific program over support for particular platforms....................................25

Supporting scientists during proposal process....................................25

Break from the model of always needing to collect core, and embrace drilling some holes that are used solely for experiments and measurements....................................26

References....................................27

Appendix 1: Workshop Participant List....................................29

Appendix 2. Workshop Agenda....................................30

Cover image illustrates a seafloor vent (Charles Fisher, Ridge2000), a recent lava flow (Dan Fornari, Ridge2000), the JOIDES Resolution drilling vessel (IODP), and the PROD seafloor drill (Benthic Geotech Pty Ltd)

SUMMARY

A workshop on Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings was held August 27-28, 2009 in Austin, Texas. The 34 participants (Appendix 1) included junior and senior scientists, engineers, and a representative from the National Science Foundation (NSF). The goals of the workshop were to: (1) revisit the technological challenges involved in drilling young ocean crust, (2) discuss new and future technologies that may overcome these challenges, (3) refine existing, and develop new scientific motivations, for drilling young ocean crust, (4) develop strategies that can lead to new drilling proposals, (5) recruit and encourage junior scientists to be involved in IODP, and (6) generate a white paper for INVEST, an international meeting held in Bremen, Germany, from September 23-26, 2009 whose focus was to define the scientific research goals of a post-IODP drilling program.

The workshop opened with an overview talk summarizing research on the mid-ocean ridge systems and global questions surrounding the importance of on- vs. off-axis processes, the seawater-crust chemical exchange and heat flux, and the diversity of subseafloor microbiology. The remainder of the morning of Day 1 was devoted to talks on the engineering and technology of ocean crustal drilling, including an overview of the history of DSDP/ODP/IODP projects, new technologies that IODP-MI is particularly focused on that might overcome previous technological challenges for drilling young ocean crust, and new seafloor drilling technologies in the hydrocarbon/minerals industry that might be relevant for the young ocean crust drilling environment. After lunch a poster session allowed participants to interact and share their ideas of scientific problems that could be addressed with seafloor drilling. Workshop participants then split into two breakout groups for the afternoon of Day 1 and morning of Day 2 to focus on hypotheses and strategies for studying: (1) active processes such as fluid flow, seismicity, and biological activity, and (2) the structure, petrology, geochemistry, and geophysical properties of young ocean crust. The two breakout groups reconvened on the afternoon of Day 2 to compile hypotheses, discuss possible projects, and articulate questions and concerns about working with IODP and ways to interface with other programs and agencies. The workshop agenda is included as Appendix 2.

The results of the workshop are presented in this report, and also summarized in a white paper to the IODP renewal-planning meeting, INVEST, in Bremen Germany, 2009. Additionally, the workshop results are synthesized with another workshop on ocean drilling of ocean crust in an article in EOS (Hayman et al., in press). We hope this report serves as a resource for workers planning scientific drilling of ocean crust.

INTRODUCTION

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 (Fig. 1), 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. Scientific ocean drilling is one of the only ways to access the ocean crust's subsurface in this critical environment. Accessing the subsurface is absolutely essential for developing and testing hypotheses rooted in the fundamentally three-dimensional nature of ocean crustal processes.

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 have 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 chemical 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.

Despite the clear need for ocean crust drilling only 9 of the 112 IODP proposals active in Spring 2009 (when the workshop proposal was developed) targeted this environment (Table 1). At the time of the workshop 3 of these proposals had been deactivated, leaving only 6 active oceanic crust proposals in the IODP system. On a more positive note, 3 of these proposals (522-Full5, 545-Full3, and 677-Full) are scheduled for drilling in 2010-2011, which reflects community support for scientific results that can be addressed by ocean crust drilling.

Table 1. Oceanic Crust IODP Proposals Active as of Spring 2009

Proposal	Short Title	Lead Proponent	Proposed Basement Penetration	Spreading Rate	Stage*
522-Full5	Superfast Spreading Crust	Teagle	>2000 m	superfast	OTF, scheduled
532-Full	Kane Megamullion	Tucholke	200 m	slow	deactivated
535-Full6	735 Deep	Dick	1000-6000 m	slow	deactivated
545-Full3	Juan de Fuca Flank Hydrogeology	Fisher	0-600 m	intermediate	OTF, scheduled
547-Full4	Oceanic Subsurface Biosphere	Fisk	150 m	Intermediate	SPC
551-Full	Hess Deep Plutonic Crust	Gillis	>300 m	Fast	SPC
584-Full2	TAG II Hydrothermal	Rona	100-250 m	Slow	deactivated
640-Full	Godzilla Mullion	Ohara	700-800 m	Slow	SSEP
677-Full	Mid-Atlantic Ridge Microbiology	Edwards	0-500 m	Slow	OTF, scheduled

*OTF = Operations Task Force; SPC = Science Planning Committee; SSEP = Science Steering and Evaluation Panel; http://www.iodp.org

SCIENTIFIC MOTIVATION

Accretion of ocean crust and properties of the axial lithosphere

The ocean crust makes up roughly two-thirds of the Earth's surface and is accreted within the axial regions of the mid-ocean ridge plate boundary system (Figs. 2, 3). The largest ocean basins were accreted within axial regions, such as the East Pacific Rise (EPR), that are at most a few kilometers wide. The EPR and other ridges such as the Juan de Fuca spread at intermediate-to-fast rates, >60 mm/yr and up to >140 mm/yr (and > 200 mm/yr in the geologic past). Underlying these localized ridge axes are seismically imaged axial magma chambers (AMCs). AMCs likely comprise high amounts of partial melt within a sill-like structure a few tens to hundreds of meters thick (Fig. 4). The nature of the lower crust below the AMC and their distribution below the axial flanks is relatively unknown, but above the AMC are ~1.5 km of Mid-Ocean Ridge Basalts (MORBs). Basalt intrusion as dikes and extrusion as flows are the most voluminous deliveries of mantle material to the crust on Earth. The magmatic and volcanic processes along mid-ocean ridges generate and dissipate enormous amounts of heat (Fig. 5). The accretionary processes combined with plate-tectonic stresses also mechanically strain the axial systems, causing fracturing and faulting [e.g., *Hayman and Karson*, 2007].

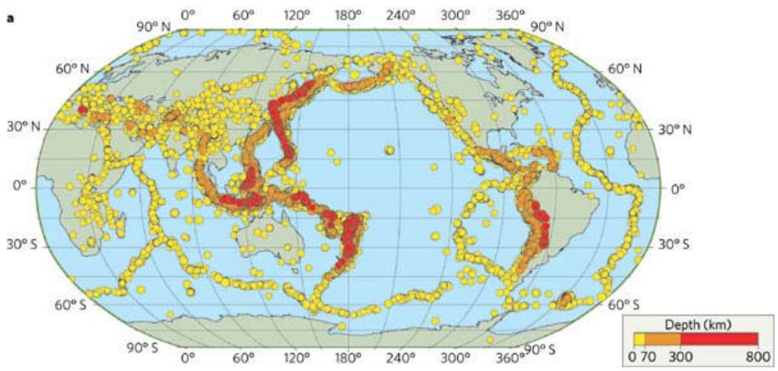


Figure 2. Worldwide distribution of earthquakes of magnitude (M_w) greater than 5.0 from 1 January 1991 to 31 December 1996 [*Romanowicz*, 2008]. Earthquakes occur mainly along plate boundaries, delineating, in particular, the global mid-ocean ridge system where ocean crust is created.

All of the mid-ocean ridge accretionary processes are being studied through the lens of geophysical techniques or interpretations of features on the seafloor. Older ocean crust has been investigated with ocean drilling, submersible access to bedrock exposures, and also in ophiolites. Yet, subsurface constraints in axial regions and near-axial regions are absent.

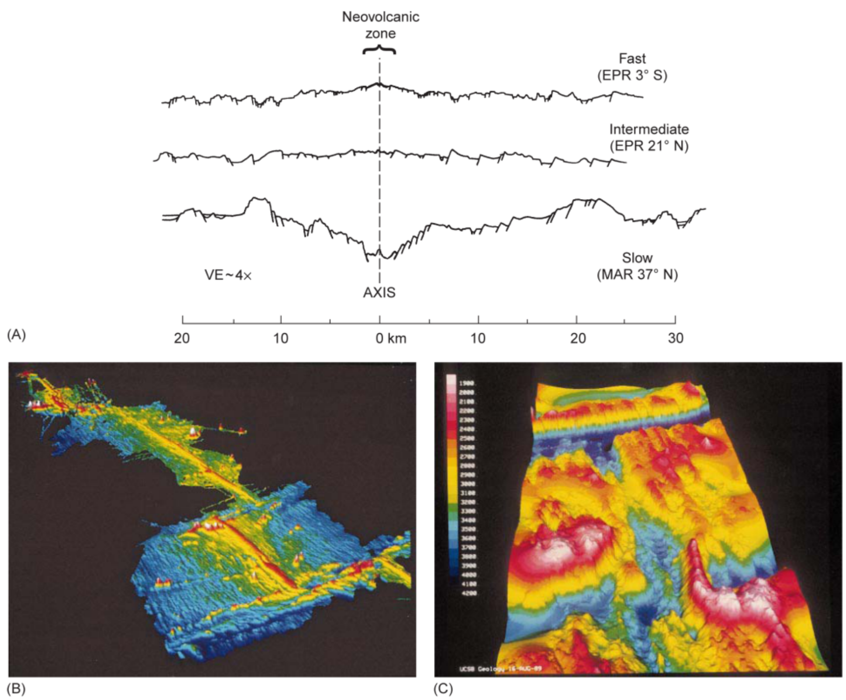


Figure 3. From *Macdonald* [2001]; comparison of fast, intermediate, and slow spreading centers. Lower left is the EPR and lower right is the Mid-Atlantic Ridge. Note how fast-spreading centers have well-developed axial highs and slower spreading centers deep axial rifts. The difference between these bathymetric characteristics reflects subsurface magmatic and tectonic processes.

Without such subsurface constraints, we cannot completely address:

a. the geochemical and petrologic variation over short time periods of young MORBs;

b. the internal structure and stratigraphy of axial volcanics;

c. the in situ stresses within spreading centers and resulting strains including diking, faulting, fracturing, and porosity variations, and their manifestations in faulting, seismicity, and hydrothermal fluid flow; and

d. the permeability and porosity of mid-ocean ridge crust;

The technological difficulty relative to the importance of scientific drilling of young ocean crust has an analogous situation in the drilling in active areas of Hawaii that produced some of our deeper understanding of crystallization processes in igneous provinces previously only inferred, controversially, from the geologic record [*Marsh*, 2006]. Successful efforts in areas such as Hawaii and also Iceland inspire renewed confidence in drilling in these challenging conditions. Moreover, ocean observatory science, currently progressing in its programmatic and technologic feasibility, will require subsurface constraints on the observed processes. It is also important to get a three-dimensional view of the structure of the ocean crust. A series of focused holes would go a long way to helping understand the detailed structure of the oceanic crust, particularly as it pertains to such processes as subsurface fluid flow.

WORKSHOP GOAL: *arrive at a clear statement of the importance and feasibility of drilling into mid-ocean ridge axial crust.*

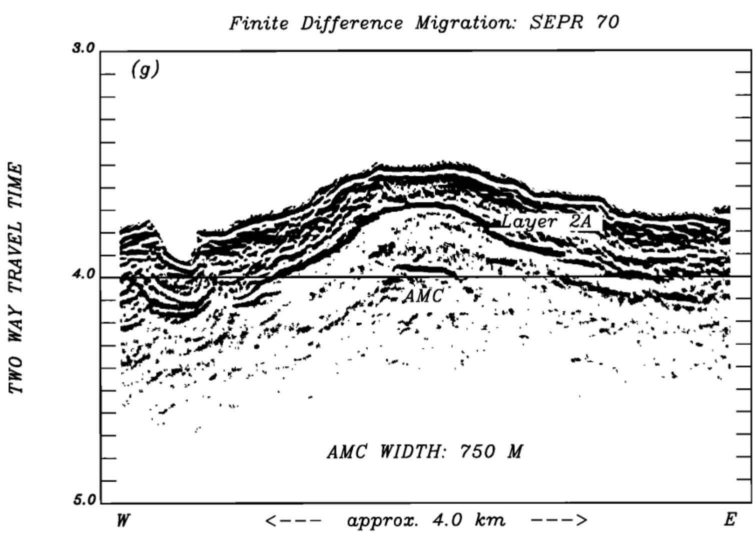


Figure 4. Seismic reflection image of the AMC in the South-East Pacific Rise [*Kent et al.*, 1994]. Processes below the AMC, in the Low-Velocity Zone, are relatively unknown and scientific drilling into the deep crust is an important component of understanding deeper crustal accretion. Above the AMC are the basaltic dikes and lavas and the axial and axial-flank hydrothermal systems. Testing hypotheses about the dynamics of these upper crustal systems will require drilling into young ocean crust.

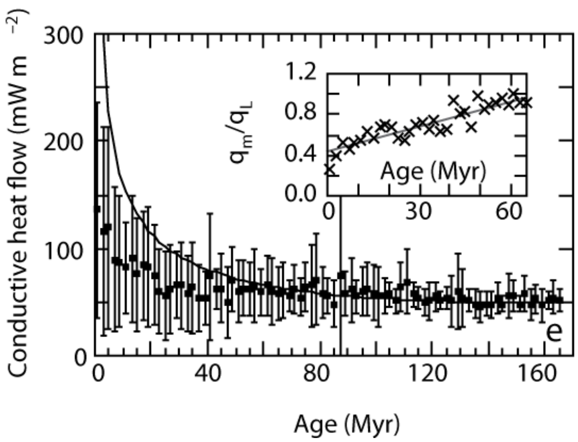


Figure 5. Heat-flow data (dots) and model (line) [*Fisher and Becker*, 2000]. The difference between measured conductive heat flow and the mdoel suggests that a great deal of heat loss of the oceanic lithosphere is advected by focused fluid flow in young (less than ~65 Ma) and particularly in very young (less than ~1 Ma) oceanic crust.

Aging of ocean crust along axial flanks

One of the perpetual questions confronting mid-ocean ridge studies is: *what happens along the axial flanks*? The axial flanks are the broad areas of the seafloor where depth increases as the crust ages and cools with seafloor spreading. Along the axial flanks heat flow drops off exponentially from the axial high (Fig. 5) [e.g., *Fisher and Becker*, 2000]. Layer 2A, the layer above a reflector inferred to be the base of the volcanic section by most workers, increases in velocity with age, potentially disappearing in older off-axis crust [*Houtz and Ewing*, 1976]. The prevailing hypothesis for the aging of Layer 2A is that seismic velocities in the upper crust increase away from the ridge axis as cracks and voids close [*Wilkens et al.*, 1991], a process that is probably closely related to hydrothermal circulation.

Some workers have estimated that ~70% of hydrothermal heat loss occurs along the ridge flanks [*Stein and Stein*, 1994], and that nearly half of hydrothermal heat loss occurs from very young seafloor <5 million years old [*Pruis and Johnson*, 2003]. In spite of the processes that must operate along axial flanks, information is scarce because of a blanket of volcanic flows and sediment, and also because these vast realms are largely unexplored. Young abyssal hills that have not yet been buried by sediments provide limited but intriguing views into axial flank processes; although there has been very little ridge flank exploration, two young EPR abyssal hill localities contain evidence of recent hydrothermal activity [*Haymon et al.*, 2005]. Ridge flanks may also have some volcanism, which could in turn drive ridge-flank fluid flow [*Alt et al.*, 1986; *Hekinian et al.*, 1985; *Mottl et al.*, 1998]. Much of this ridge flank activity could potentially be driven by off-axis melt lenses [*Durant and Toomey, 2009*]. Without subsurface constraints we cannot further address or attain:

a. heat flow beneath the volcanic and sedimentary cover the axial flanks;

b. evolution of permeability and porosity in the critical interval of <1 Ma crust;

c. an assessment of the thickness and character of axial flank lava flows;

d. a groundtruth for the evolution of seismic velocities in the ocean crust;

e. an understanding of the initiation and slip on abyssal hill faults; and

f. an understanding of how ridge hydrothermal systems evolve from ridge-crest circulation to ridge-flank circulation.

Drilling into axial flanks has already been accomplished in shallow holes along the Juan de Fuca Ridge [*Shipboard Scientific Party*, 2004]. These holes were drilled as part of an overall observatory strategy to determine *in situ* permeability of the crust in pursuit of many of the fore-mentioned scientific problems.

WORKSHOP GOAL*: elucidate the current state of knowledge of axial-flank processes, and develop a statement of how ocean drilling can uniquely contribute to understanding the aging of the ocean lithosphere.*

Hydrothermal Processes

Hydrothermal fluid flow is the most significant mechanism for crustal heat loss and chemical exchange between seawater and the crust. Hydrothermal fluids transport at least 34% of the heat from young ocean crust [*Stein and Stein*, 1994], and a large proportion of that advection occurs by focused fluid flow that manifests itself in vents along the seafloor. The high fluid fluxes and local enrichment of chemical species at vents are responsible for their importance as economic mineral deposits (in ophiolites, for example), and also to sustain thriving biological communities in modern systems. Earthquake seismicity and dike-intrusion events are linked with hydrothermal discharge in some ridge segments [*Delaney et al.*, 1998; *Embley and Chadwick*, 1994; *Haymon et al.*, 1991; *Haymon et al.*, 1993; *Tolstoy et al.*, 2006], further showing that hydrothermal fluid flow is linked to a range of axial mechanical processes.

The volatility of mid-ocean ridge hydrothermal systems is partly a curse to understanding subsurface processes. The high fluid fluxes generally prevent equilibrium between the crust and fluids, thereby restricting the information we can gain about the deeper hydrothermal system from the vent fluids [e.g., *Wells and Ghiorso*, 1991]. Though many hydrothermal systems can be related to fissures or faults in the upper veneer of the axial and axial flank lavas, the underlying structure of such systems are concealed and thus the mechanisms for fluid flow (e.g., faulting, fracturing, or pore-fluid flow) can be difficult to identify uniquely.

Subsurface investigations of active or inactive vent fields would allow us to determine the:

a. compositions of fluids and rocks beneath hydrothermal vents;

b. crustal permeability & porosity below/around vents;

c. the relative importance of focussed fluid flow relative to unfocussed fluid flow, and the composition of lower temperature fluids in the shallow circulation that supports most of the subsurface microbes;

d. relationship between fluid flow, heat flow, seismicity, and volcanism; and

e. limits of biologic activity in hydrothermal areas.

As explored below, these hydrothermal systems are the sites of incredible biologic diversity. Microbial activity can affect porosity, fluid flow, and chemistry of subseafloor fluids and minerals, and therefore is expected to play an enormous role in the development of hydrothermal systems. Hydrothermal system are also complicated by the separation of brines but where they ultimately reside in the subsurface remains unknown. In such disequilibrium conditions anhydrite and quartz precipitation are enhanced and clog porosity and permeability. Detailed sampling of hydrothermal systems by scientific drilling is likely the best way to understand these critical interactions between microbes and fluid-vapor and water-rock interactions. These interactions are a central theme of many observatory efforts for mid-ocean ridge systems.

WORKSHOP GOAL: define the feasibility of sampling rocks, minerals, and fluids beneath hydrothermal systems, and how to integrate such approaches with observatory science and geological investigations of altered ocean crust.

Ocean crust ecology

One of the most striking aspects of ocean crust is the diversity of subsurface biota. For example, basaltic lavas from the EPR have a higher bacterial richness of species than any other marine environment (Fig.6). Entirely new *phyla* have been discovered in hydrothermal vents, and many have argued that the cradle of life on Earth - and potentially other planets - was in an environment similar to what we see in modern mid-ocean ridge vents. There are significant questions about the nature of mid-ocean ridge ecosystems that can best, or in some instances only, be addressed by scientific drilling:

a. What is the diversity of *subsurface* biota?

b. What are the physical controls on subsurface diversity (e.g., permeability, porosity, distribution of high thermal and chemical gradients, etc.)?

c. What is the spatial distribution of subsurface biota in the ocean crust?

d. What is the highest temperature at which life in these environments can exist?

e. What is the range of chemical conditions that supports subsurface biota?

These basic questions are not even at the level of the more intricate interactions that must occur within the mid-ocean ridge ecosystem. Yet, placing better bounds on the conditions in which these ecosystems thrive is a major impediment to scientific progress. There are no direct measurements or observations of the subsurface microbial biosphere in ocean crust/hydrothermal areas. All of what we know is inferred from 'snowblowers' or vents, and collection of microbial mats from ridge flank abyssal hill fault scarps [*Ehrhardt et al.*, 2007].

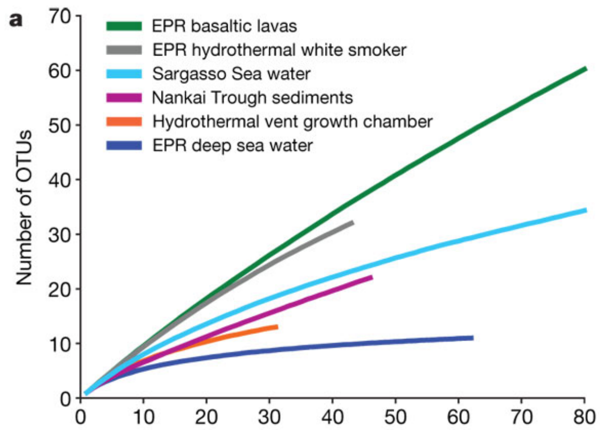


Figure 6. Diversity of microbial life in different oceanic environments [*Santelli et al.*, 2008]. Biodiversity is greatest along the EPR-flank basaltic crust relative to other deep-sea settings.

WORKSHOP GOAL: evaluate ocean drilling approaches and technological challenges in pursuit of ecosystem questions

TECHNOLOGY: CHALLENGES AND SOLUTIONS

The workshop started off with 2 invited talks designed to educate the participants on the challenges and possible solutions for drilling young oceanic crust. Jay Miller gave a presentation summarizing the history of ocean crust drilling, and presented some of the technological accomplishments of these drilling legs. He also presented some of the problems encountered during ocean crust drilling, and some possible solutions to overcome these problems. Leon Holloway then gave an impromptu presentation on seafloor drills and their possible use in drilling ocean crust. Finally Greg Myers gave a presentation on technological developments currently being evaluated by IODP, with an emphasis on techniques that could be applicable to young ocean crust drilling.

Presentation: Jay Miller, 'Historical Developments in Scientific Drilling on and About Mid-Ocean Ridges'

Table 2 presents a table that illustrates the timeline of drilling ocean crust basaltic basement. It includes examples of the challenges (e.g., Legs 54 and 142) and the accomplishments (e.g., Legs 301, 312) of drilling in this challenging environment. Key lessons learned through the history of ocean drilling is that it takes 4-5 attempts for one successful entry to 50-100 m depth into young ocean crust. When drilling stops, problems develop. Lastly, coring the upper 50-100 m in young fractured ocean crust is so far unachievable.

Table 2. Basaltic Basement Drilling

Year	Phase	Leg	Target, Remarks
1968-1972	DSDP	16, 24	Early DSDP legs recovered basalts.
1970	DSDP	15	First operational reentry
1974	DSDP	34	First attempt at deep basement penetration in Pacific crust (16 Ma crust near EPR)
1974	DSDP	37	Drilled MAR Crust, penetrated 583 m basement at site 332B
1977	DSDP	54	Attempt to drill deep-penetration re-entry site into young (<5 Ma) Pacific crust. Learned that young sheet flows difficult to drill with conventional rotary drilling; deepest basement penetration was 52.5 m.
1979	DSDP	64, 65	Drilled young crust in Gulf of California
1979	DSDP	69	Drilling started on Hole 504B, intermediate-spreading crust
1979	DSDP	70	Attempt to drill young crust at Galapagos Spreading Center; maximum basement penetration 10 m and core recovery <7%
1981	DSDP	82	MAR flank drilling
1985	ODP	106, 109	Cored zero-age MAR crust. New 'hard formation' coring bits. Bare rock spud using hard-rock guidebase (HRB).
1989-1990	ODP	129	Drilled old Pacific crust, 130 m into Jurassic basement.
1989-1990	ODP	124E, 132	Tested diamond coring system (DCS). Drilled 79 m of zero-age fractured basalts at Sumisu Rift (incipient back-arc basin)
1992	ODP	142	Diamond coring system test at zero-age crust on the EPR. Technical problems with secondary heave compensation for the DCS resulted in <10 m cored section.
1991, 1996	ODP	139, 168	Successful drilling on Juan de Fuca eastern sedimented flank
2002	ODP	205	Drilling started at Hole 1256D, superfast-spreading crust
2003	ODP	209	Drilling of MAR 15°20'N recovered some young basalts (although target was mantle peridotite).
2004	IODP	301	Successful drilling on Juan de Fuca eastern sedimented flank. 2 new basement holes 108 and 320 m into basement instrumented with multilevel CORK observatories.
2005	IODP	309, 312	Drilling at Hole 1256D reaches gabbro

The difficulties of drilling young ocean crust are reflected in Fig. 7, which plots basement age and depth of penetration for holes >50 m into crust formed at mid-ocean ridges. No holes have penetrated >200 m in crust <3 Ma, which is a critical region where active volcanic, hydrothermal, and structural processes are expected to occur. There is also a large gap between 20-110 Ma.

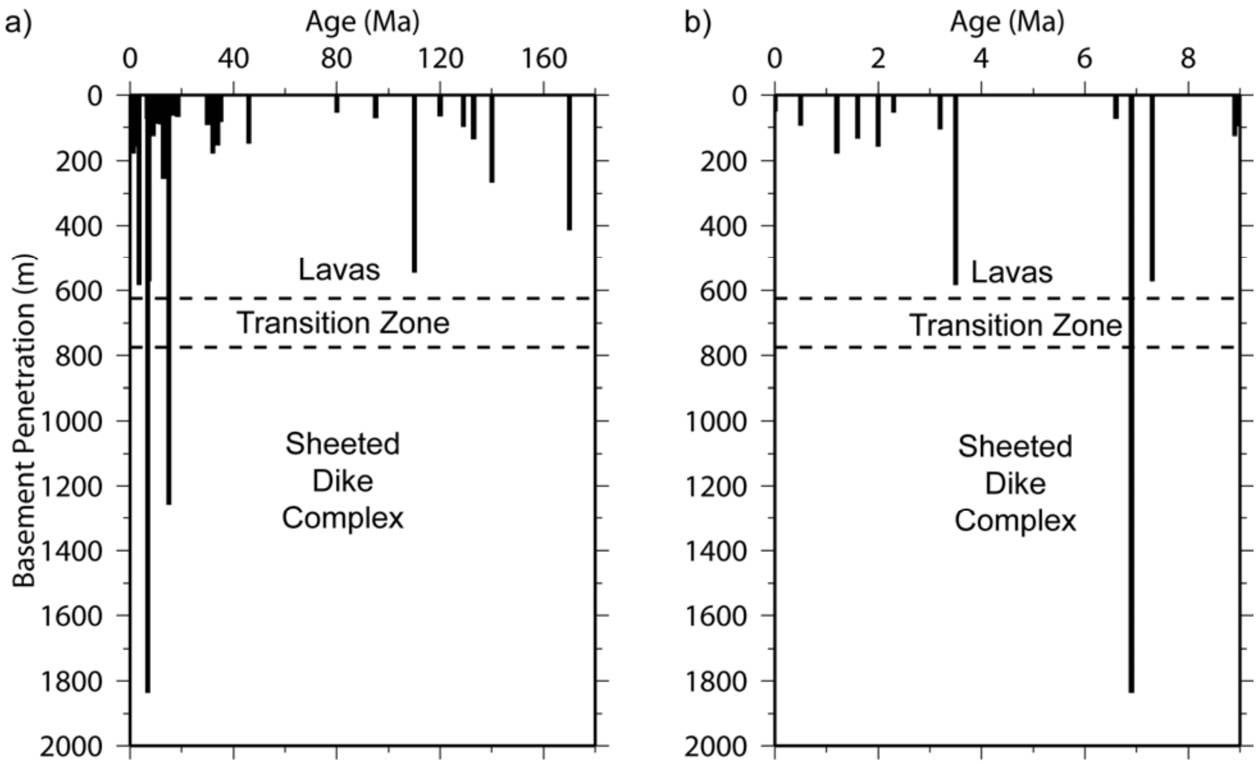


Figure 7. Basement age and depth of penetration for scientific drill holes deeper than 50 m drilled into in situ ocean crust formed at mid-ocean ridges. Note the boundaries between the erupted lavas, dike-lava transition zone, and the sheeted dike complex/upper gabbro boundary are placed at arbitrary depths based loosely on the Hole 504B stratigraphy.a) Ages 0-180 Ma. b) Ages 0-9 Ma. From *Wilson et al.* [2003]

Technologies likely required for drilling young mid-ocean ridge crust are:

a. Reentry capability
b. Diamond coring
c. Weight-on-bit control
d. High-temperature tools

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 (Fig. 8). 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. In addition, previous attempts to set casing in basalt have been unsuccessful. However a ring bit has worked well in gabbro, but remains untested in basalt.

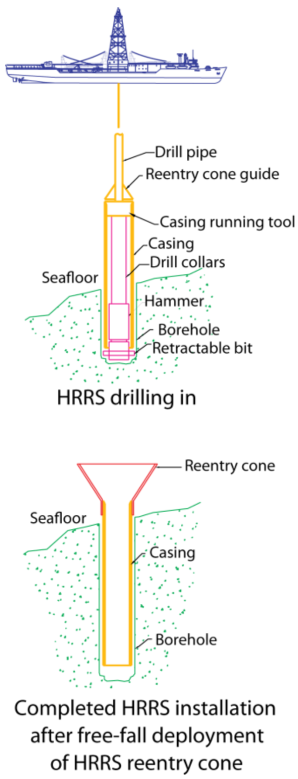


Figure 8. Schematic of the HRRS in the Hammer Drill-In-Casing mode. The hammer drill is run inside the casing and simultaneously drills a hole and advances the casing. A reentry cone is free-fall deployed, and the hammer drill is withdrawn from the casing leaving a reentry installation. Figure from IODP.

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.

Weight-on-bit control is essential for successful drilling using the ADCB system. The active heave compensation system was removed from the JOIDES Resolution during the recent refit. However, the refitted passive heave system should result in a more stable platform. Testing is presently underway with this system, but the drilling engineers think there has been a dramatic improvement. The Chikyu may have a better weight-on-bit control than the JOIDES Resolution, but this has not yet been confirmed.

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. The temperature limit for most commercial logging tools is less than 150°C. Recent drilling in Iceland demonstrates that holes can be kept cool enough for drilling, but not necessarily for logging operations.

Presentation: Leon Holloway, 'Seafloor Drills'

Newly developed remotely-operated submersible drill rigs (Fig. 9) can drill the upper 100-150 m with good core recovery. By placing the drill rig directly on the seafloor the weight-on-bit variations are minimal, which allows use of diamond coring systems. These drills could be used in conjunction with the hard rock reentry system, which provides no core recovery in the cased interval. Another application would be site surveys. Several types of submersible drill rigs are rated to depths of 3000-4000 m.

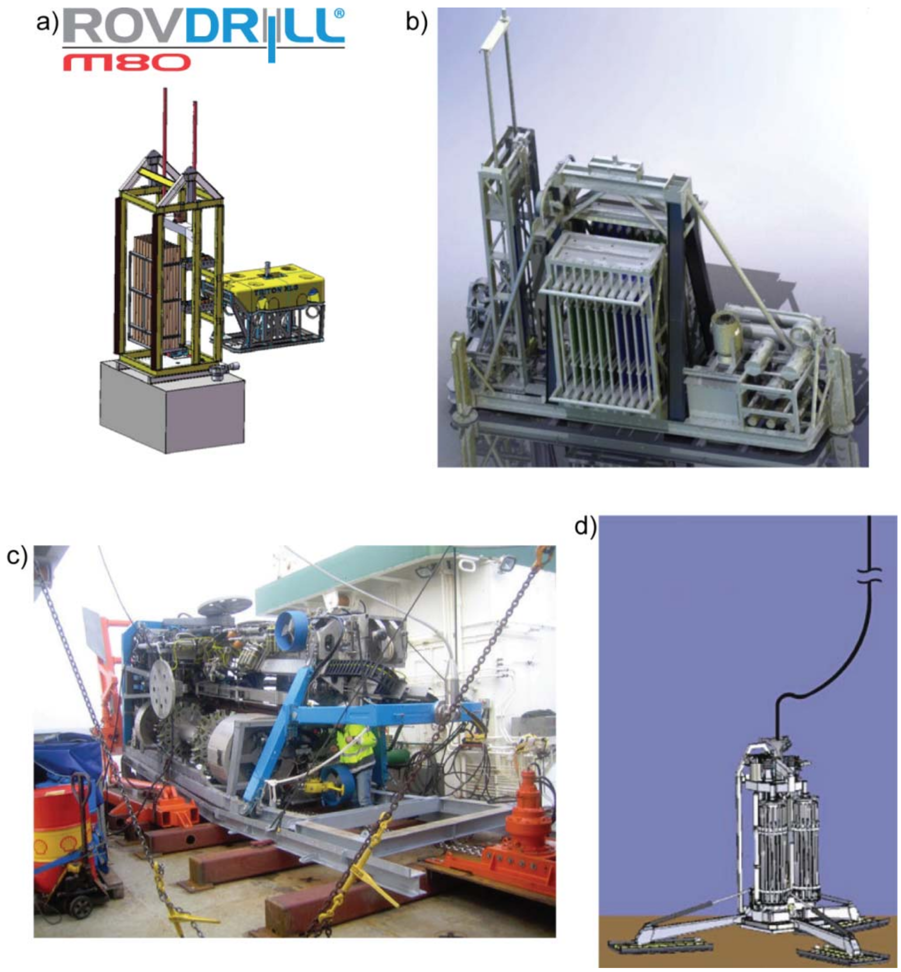


Figure 9. Seafloor drills. a) Seafloor Geosciences Inc. Rovdrill M80. b) Williamson Deep Water Automated Coring System. c) Marum MeBo. d) Benthic Geotech PROD.

Seafloor Geoservices Inc. Rovdrill M80. This is a subsea drilling system designed to take geological core samples in a variety of seabed environments including hard-rock. The maximum working depth is equal to the depth rating of the support ROV. Coring depth is 80 m standard, expandable to 160 m, with a core diameter of 3". It can be mobilized on a variety of vessels.

Williamson Deep Water Automated Coring System (DWAC). This drilling system operates on the seabed from ships of opportunity over an umbilical supplying mechanical, electrical, and telemetry needs. It can operate in depths up to 4000 m and will do continuous sampling to depths of 150 m. The sampling tool diameter is 3".

Marum MeBo. Developed by the Center for Marine Environmental Sciences at the University of Bremen. This drill rig is capable of sampling soft sediments and hard rocks down to 70 m, and can operate in water depths up to 2000 m. It can be deployed from standard research vessels and uses an umbilical for energy supply and communication. Core diameter is 74-84 mm for conventional drilling, and 57-63 mm for wire line drilling.

Benthic Geotech PROD. This is a fully self contained, remotely operated sea floor drilling system that is powered and controlled from a ship via an umbilical. It can operate in water depths up to 2000 m and penetrate up to 125 m. Core diameter is 44 mm for the piston sampler and 35 mm for the rotary diamond drill.

Presentation: Greg Myers, 'Engineering to Support Transformative Science'

The goals for drilling young ocean crust are inline with the primary IODP engineering goals:

a. Increasing the quantity and quality of acquired core
b. Increasing the borehole depth achieved

Technology gaps that are relevant to drilling young ocean crust include:

a. Recovery % improvement is critical in all borehole depths
b. Reliable hard rock spudding and reentry
c. Ability to operate in water temperature >200°C

There are four main focus areas for achieving solutions to these techology gaps:

a. Drillstring stabilization
b. Spudding and reentry
c. High temperature
d. Borehole management

Drillstring stabilization techniques. 1) The bottom-hole assembly (BHA) bumper sub is used to decouple the ship's heave motion from the bit; it has largely been supplanted by the heave compensator and is seldom used in modern operations. However, enhancements can be made. 2) Passive heave compensation is presently installed on the Joides Resolution. It was refurbished in dry dock, and anecdotal evidence suggests an improvement in core quality and quantity. 3) Active heave compensation is presently installed on the Chikyu. The effectiveness of the system is under investigation, but it appears to be providing a significant benefit. 4) Seafloor mounted drillstring stabilization is still conceptual, but is likely to be the most effective technological approach. However, it must be developed, and is likely to be expensive.

Spudding and reentry. 1) Coring and bit technology include high temperature bits that are under development by CDEX, and retractable bit technology. 2) Operational techniques have not been developed or utilized, but could include using a ROV to identify and prepare the site prior to mobilization of the drill rig by setting up a sub-sea infrastructure. 3) The hard rock re-entry system (HRRS) current design installs a single string of 16" casing to shallow sub seafloor depths (<30 m). An improved theoretical design using dual hammers could install the system deeper and isolate more of the unstable upper crust of young basalt flows. 4) Seabed coring devices could capture the uppermost 0-150 m of the seafloor.

High temperature. High quality drilling muds become ineffective beyond 200°C; extreme logging tools will not operate beyond 250°C for more than a few hours; bits and core barrels will fail at high temperatures. The IODP technology roadmap includes 3 areas to pursue regarding high temperatures: 1) Temperature tolerant muds and drilling bits. 2) High temperature electronics, sensors, and sensor systems. 3) Accurate estimates of downhole termperatures.

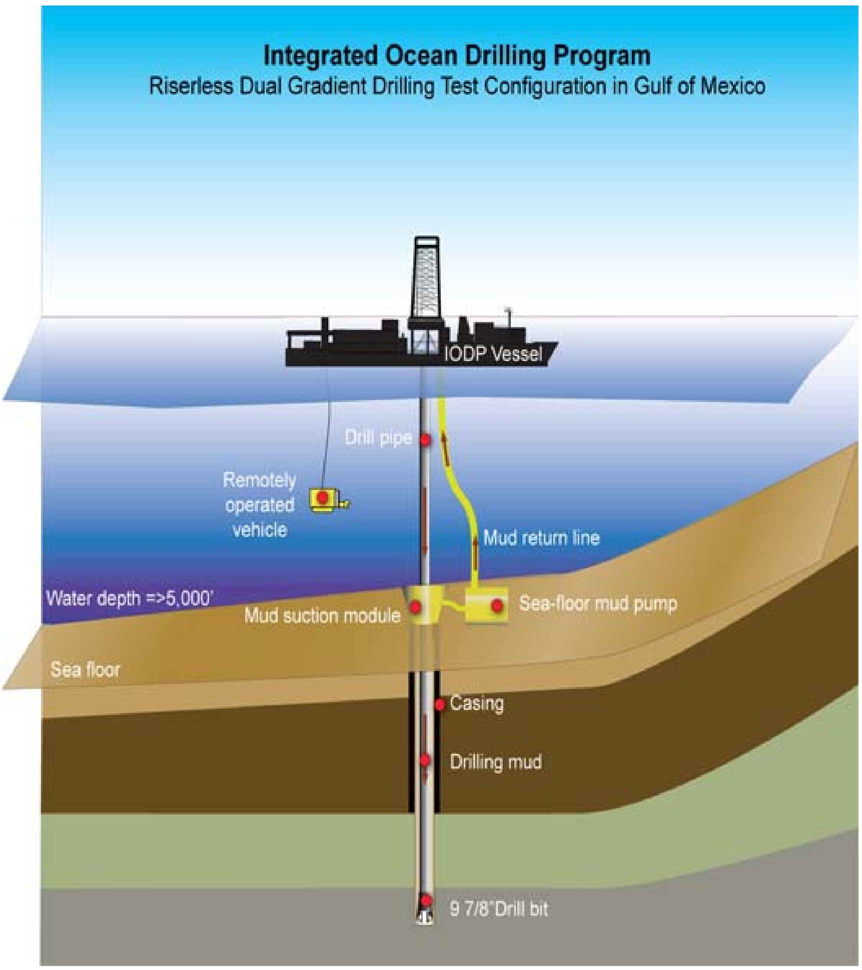


Figure 10. Riserless mud recovery system which will eliminate mud and cuttings discharge at the seafloor and provide a cost-saving mud-control technique in the top hole section of ultra deepwater wells.

Borehole management. To avoid borehole collapse, engineered mud must be circulated continuously as part of a comprehensive plan to drill deeply. <u>Using engineered mud is likely the single most important technological improvement that can be made.</u> Existing riserless drilling on the Joides Resolution sometimes uses engineering mud, but it is expensive because it is pumped and then dumped onto the seafloor. Riser drilling on the Chikyu does use a complete mud circulation system. An emerging technology is riserless mud recovery (Fig. 10), which has mud circulation without blowout prevention and could be used on the Joides Resolution. IODP-MI is working with the oil and gas industry in the DeepStar project to develop this technology on an IODP platform in water depths >1600 m; sea trials may be targeted as early as mid FY2011.

Summary of Technological Advances and Engineering Challenges

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.

Riserless mud recovery is an emerging technology that will provide improved wellbore stability. The community is excited about the DeepStar project that is partnering with industry to develop this technology for deepwater drilling.

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.

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.

BREAKOUT GROUP: PHYSICAL PROPERTIES OF OCEANIC CRUST

The physical properties breakout group focused on the formation and maturation of oceanic crust from the axis to the flanks. The group first compiled a series of hypotheses, and then developed 3 potential drilling programs that could test many of the hypotheses.

Hypotheses: 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 persist through time, or alternatively they are ephemeral and in many instances not well preserved.

Potential Drilling Program: Transect of Multiple Holes on a Flowline

- For maximum return, this program should be located at a well-characterized section of the mid-ocean ridge system. Either the Juan de Fuca or EPR Integrated Study Site (ISS) would be ideal candidates.

- Some scientific questions that could be addressed include the nature of magmatic-tectonic construction, the underlying cause of the seismic layer 2A/2B boundary, hydrothermal alteration, and crustal magnetization.

- Seafloor drilling targeting the upper 100 m could serve as a site survey for deeper holes.

- 3 holes at various ages would constrain maturation processes. There was not consensus on exact ages, but many were in favor of 0, 0.5, and 2.0 Ma.

- The breakout group noted that this program might be addressing the same questions that have been around for decades, but that we now have better context and drilling technology to achieve scientific objectives.

Potential Drilling Program: Target upflow and downflow crust along and across axis

- Seismicity and magnetization could be used to identify “hot” and “cold” regions.

- Some scientific questions that could be addressed include the effect of the thermal regime on alteration in the underlying crust and the depth and extent of hydrothermal systems.

- Seafloor drilling targeting the upper 100 m could serve as a site survey for deeper holes. This target interval is important because it is where pristine fluids meet sea water, and the drilling technology is finally available to core this important interval.

- The breakout group agreed that this is a frontier area of research.

Potential Drilling Program: How does observed spatial variability at the seafloor relate to deeper processes?

- Target a site where there is activity: off-axis seamount, abyssal hill, near-axis or off-axis vent.
- How do near-axis volcanoes vary compositionally compared to ridge crest crust?
- How does faulting develop in an abyssal hill, and how does faulting interact with magmatic and hydrothermal systems?
- Can we quantify heat loss through drilling? Can we constrain modes and mechanisms of heat flow?

BREAKOUT GROUP: ACTIVE PROCESSES AT MID-OCEAN RIDGES

The active processes breakout group emphasized hydrothermal and biological processes, and focused on data that are derived from a broad suite of down-hole data, which in some cases do not require core acqusition. The group developed a list of hypotheses testable by drilling, and also discussed policy changes within the current drilling program that could facilitate breakthrough science.

Hypotheses: 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 $>125^{o}$C.

- 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.

SUPPORTING THE SCIENCE AND THE SCIENTISTS

Drilling objectives in fractured, crystalline rock present a number of challenges. The organizational structure of IODP is not currently configured in a way that facilitates the type of support for engineering development and testing that would encourage proposals to fully develop hard-rock drilling capability. We suggest ways in which support for engineering development and engagement of young scientists could be improved.

Engineering support and scientific input

- Commit to developing the technology needed to sample microbes and fluids.
- Tools and sensors for high temperature (>200ºC) studies.
- Create more direct linkages and dialogue between science proponents and the engineering support. Scientists need to know what's feasible in order to write good proposals; engineers and managers must know what's desired by the scientific community to develop better tools and approache.
- Increase reserved engineering time on each drill leg, and fully utilize all engineering time for testing new tools and technology rated highest by the scientific community.

Scientific program over support for particular platforms

- Broaden support to include different kinds of drills (e.g. seabed drills) and drilling platforms.
- Change to proposals being driven by science goals rather than the need to support particular platforms/tools.
- Scientists can write proposals about the scientific objectives *without needing to be fully versed in the technology of drilling.*
- Drilling personnel can use their expertise to bring/develop/rent *full range of drilling technology needed to achieve science objectives*.

Supporting scientists during proposal process

- Problems specific to U.S. System such as supporting soft-money scientists
- Bring younger scientists in as co-PIs / ask more junior scientists to get involved
- Improve cooperation between continental and ocean drilling when there are overlapping science objectives

Break from the model of always needing to collect core, and embrace drilling some holes that are used solely for experiments and measurements

- can drill out deeper into hard rock that is difficult to core
- can avoid compromising collection of some types of data/samples
- can install instruments and take side cores to get some rock samples too
- can make wider holes to accommodate instruments and experiments
- cuttings from riser drilling or riserless recovery system allow a coarse stratigraphy to be developed that is sufficient for most hard-rock drilling

REFERENCES

Alt, J. C., J. Honnorez, C. Laverne, and R. Emmermann (1986), Hydrothermal alteration of a 1 km section through the upper oceanic crust, deep sea drilling project hole 504B: Mineralogy, chemistry, and evolution of seawater-basalt interactions, *J. Geophys. Res.*, *91*, 10309-10335.

Delaney, J. R., D. S. Kelley, M. D. Lilley, D. A. Butterfield, J. A. Baross, R. W. Embley, and M. Summit (1998), The quantum event of oceanic crustal accretion: Impacts of diking at mid-ocean ridges, *Science*, *281*, 222-230.

Ehrhardt, C. J., R. M. Haymon, M. G. Lamontagne, and P. A. Holden (2007), Evidence for hydrothermal Archea within the basaltic flanks of the East Pacific Rise, *Environ. Microbiol., 9*, 900-912, DOI: 10.1111/j.1462-2920.2006.01211.x.

Embley, R. W., and W. W. Chadwick, Jr. (1994), Volcanic and hydrothermal processes associated with a recent phase of seafloor spreading at the northern Cleft segment: Juan de Fuca Ridge, *J. Geophys. Res.*, *99*, 4741-4760.

Fisher, A. T., and K. Becker (2000), Channelized fluid flow in oceanic crust reconciles heat-flow and permeability data, *Nature*, *403*, 71-74.

Hayman, N. W., and J. A. Karson (2007), Faults and damage zones in fast-spread crust exposed on the north wall of the Hess Deep Rift: Conduits and seals in seafloor hydrothermal systems, *Geochem. Geophys. Geosyst., 8*, Q100002, DOI: 10.1029/2007GC001623.

Haymon, R. M., D. J. Fornari, M. H. Edwards, S. Carbotte, D. Wright, and K. Macdonald (1991), Hydrothermal vent distribution along the East Pacific Rise crest (9°09'-54'N) and its relationship to magmatic and tectonic processes on fast-spreading mid-ocean ridges, *Earth Planet. Sci. Lett.*, *104*, 513-534.

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

Haymon, R. M., K. C. Macdonald, S. B. Benjamin, and C. J. Ehrhardt (2005), Manifestations of hydrothermal discharge from young abyssal hills on fast-spreading East Pacific Rise flank, *Geology*, *33*, 153-156.

Hekinian, R., J. M. Auzende, J. Francheteau, P. Gente, W. B. F. Ryan, and E. Kappel (1985), Offset spreading centers near 12°53'N on the East Pacific Rise: Submersible observations and composition of the volcanics, *Mar. Geophys. Res., 7*, 359-377.

Houtz, R., and J. I. Ewing (1976), Upper crustal structure as a function of plate age, *J. Geophys. Res.*, *81*, 2490-2498.

Kent, G. M., A. J. Harding, J. A. Orcutt, R. S. Detrick, J. C. Mutter, and P. Buhl (1994), Uniform accretion of oceanic crust south of the Garrett transform at 14°15'S on the East Pacific Rise, *J. Geophys. Res.*, *99*, 9097-9116.

Macdonald, K. C. (2001), Mid-ocean ridge tectonics, in *Encyclopedia of Ocean Sciences*, edited by J. Steele, S. Thorpe and K. Turekian, pp. 1798-1813, Academic Press.

Marsh, B. D. (2006), Dynamics of magmatic systems, *Elements*, *2*, 287-292.

Mottl, M. J., et al. (1998), Warm springs discovered on 3.5 Ma oceanic crust, eastern flank of the Juan de Fuca Ridge, *Geology*, *26*, 51-54.
Pruis, M. J., and H. P. Johnson (2003), Tapping into the sub-seafloor: examining diffuse flow and temperature from an active seamount on the Juan de Fuca Ridge, *Earth Planet. Sci. Lett., 217*, 379-388.
Romanowicz, B. (2008), Using seismic waves to image Earth's internal structure, *Nature, 451*, 266-268, DOI: 10.1038/nature06583.
Santelli, C. M., B. N. Orcutt, E. Banning, W. Bach, C. L. Moyer, M. L. Sogin, H. Staudigel, and K. J. Edwards (2008), Abundance and diversity of microbial life in ocean crust, *Nature*, *453*, 653-656, 10.1038/nature06899: 10.1038/nature06899.
Shipboard Scientific Party (2004), Juan de Fuca hydrogeology: The hydrogeologic architecture of basaltic oceanic crust: compartmentalization, anisotropy, microbiology, and crustal-scale properties on the eastern flank of Juan de Fuca Ridge, eastern Pacific Ocean, *IODP Prel. Rept., 301*, DOI: 10:2204/iodp.pr.301.2004.
Stein, C. A., and S. Stein (1994), Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow, *J. Geophys. Res.*, *99*, 3081-3096.
Tolstoy, M., et al. (2006), A sea-floor spreading event captured by seismometers, *Science*, *314*, 1920-1922.
Wells, J. T., and M. S. Ghiorso (1991), Coupled fluid flow and reaction in the mid-ocean ridge hydrothermal system: the behavior of silica, *Geochim. Cosmochem.*, *55*, 2467-2481.
Wilkens, R. H., G. J. Fryer, and J. Karsten (1991), Evolution of porosity and seismic structure of upper oceanic crust: Importance of aspect ratios, *J. Geophys. Res.*, *96*, 17981-17995.
Wilson, D. S., D. A. H. Teagle, G. D. Acton, and et al. (2003), *Proc. ODP, Init. Repts., 206*, 396 pp., Ocean Drilling Program, College Station, TX.

APPENDIX 1: WORKSHOP PARTICIPANT LIST

First Name	Last Name	Institution
Keir	Becker	University of Miami
Michael	Bizimis	University of South Carolina
Del	Bohnenstiehl	North Carolina State University
Julie	Bowles	University of Minnesota
Gail	Christeson	University of Texas at Austin
David	Christie	University of Alaska Fairbanks
Jordan	Clark	University of California, Santa Barbara
James	Cochran	Columbia University, LDEO
Dionysis	Foustoukos	Carnegie Institution of Washington
Joerg	Geldmacher	IODP-USIO
Lisa	Gilbert	Williams College
Stephen	Goodyear	University of Texas at Austin
Ron	Grout	IODP-USIO
Nicholas	Hayman	University of Texas at Austin
Rachel	Haymon	University of California, Santa Barbara
G. Leon	Holloway	ConocoPhilips
Julia	Howell	University of South Carolina
Jeffrey	Karson	Syracuse University
Susan	Lang	University of California, San Diego
Marvin	Lilley	University of Washington
Jill	McDermott	University of New Hampshire
Jay	Miller	IODP-USIO
Greg	Myers	IODP-MI
Michael	Perfit	University of Florida
Richard	Peterson	Coastal Carolina University
Ian	Ridley	US Geological Survey
Julie	Robidart	University of California, Santa Cruz
Karyn	Rogers	University of Missouri
Mitchell	Schulte	University of Missouri
Stefan	Sievert	Woods Hole Oceanographic Institution
Maya	Tolstoy	Columbia University, LDEO
Masako	Tominaga	Texas A&M University
Scott	White	University of South Carolina
Robert	Zierenberg	University of California, Davis

APPENDIX 2. WORKSHOP AGENDA.

Day 1, August 27

8:30 Welcome and logistics
8:40 Welcome from UTIG director Terry Quinn
8:50 Overview of workshop goals
9:30 Jay Miller 'Historical Developments in Scientific Drilling on and About Mid-Ocean Ridges'
10:00 Discussion – what are the challenges and successes with drilling on ridges and ridge flanks?
10:30 Coffee break
10:45 Greg Myers 'Engineering to Support Transformative Science'
11:15 Discussion - What technology is available and what needs to be developed for successful drilling on ridges and ridge flanks?
12:00 Lunch
1:00 Poster Session
2:45 Coffee break
3:00 Introduction to Breakout groups

a. Physical Properties (seismic velocity, porosity, magnetics, etc.) and Geologic Structure (composition and structure of crust)
b. Dynamic Processes (direct measurement of fluid flow, geobiology)

5:00 Return to hotel
6:00 Meet in hotel lobby – group dinner at County Line BBQ

Day 2, August 28

8:30-10:00: Report from breakout groups and discussion
10:00-10:30: Strategies for IODP Proposal Development
10:30-10:45: Coffee break
10:45-12:00: Return to Breakout groups, reach agreement on major objectives, and strategies
12:00-1:00: lunch
1:00-1:30: Final presentations from breakout groups
1:30-5:30 (with coffee at 2:45): "town-hall meeting"

1. Major science statements for drilling of young ocean crust
2. Statement of technological challenges and strategies for success
3. Summarize and finalize 1 & 2 for White paper for INVEST and beyond – plan
4. Discussion of future drilling proposals & plan for proposal development