Mission Moho

Formation and Evolution of Oceanic Lithosphere

Sept 7-9, 2006, Portland, Oregon, USA

An international workshop sponsored by
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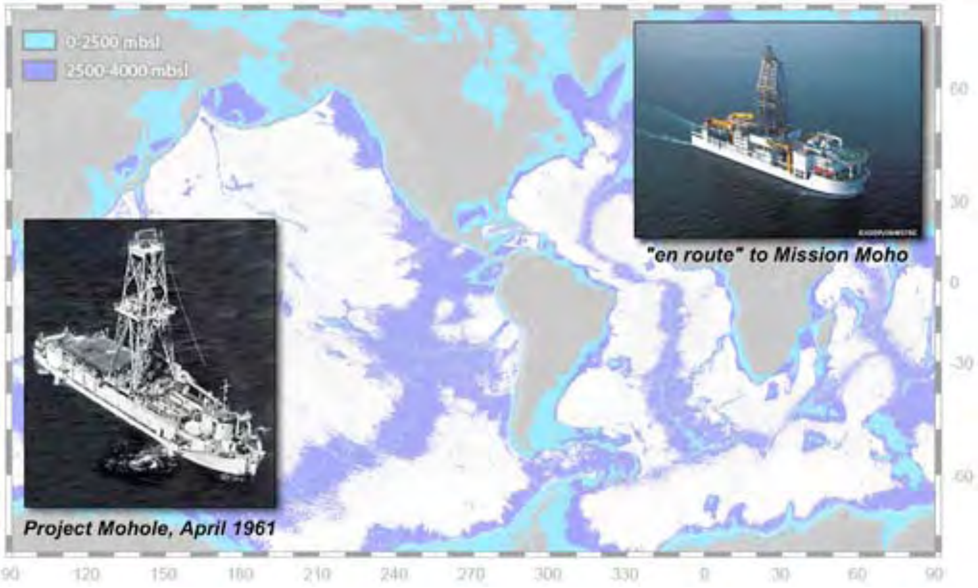

"en route" to Mission Moho

Project Mohole, April 1961

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MISSION MOHO

The dominant geologic process on planet Earth is creation of new oceanic crust, which hosts life and holds the history of Earth origin and evolution. The Moho is a seismic boundary assumed to represent the frontier between the crust and the mantle. We have not yet crossed this frontier, and the mission is primarily to determine the nature of the Moho. To drill and sample through crust into the mantle, is to understand the process of planetary renewal and how the surface of Earth is paved. The journey across this frontier and beyond into the Earth's mantle, the driver of plate tectonics, will take us through the primal architecture of this planet.

Mission Moho will build upon and utilize new technologies to achieve the long-term (40 yr) goal of drilling to the mantle, which was the inspiration for scientific ocean drilling. The ability to conduct this mission through the IODP international partnership will create a legacy for generations to come.

-- Participants' summary statement

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EXECUTIVE SUMMARY

Mission Moho presents IODP with a bold technical challenge – to achieve a quantum increase in our understanding of Earth evolution by drilling from the seafloor, through the ocean crust, through the Moho, and into the uppermost mantle.

Background

The formation and evolution of the oceanic lithosphere is the dominant process in the chemical differentiation and physical evolution of our planet. Plate tectonic processes completely repave the ocean basins every 100-200 million years (more than 50 times in the history of the earth). Lithosphere formation encompasses the transfer and transformation of material and energy from Earth's mantle to the crust and from the crust to the ocean and atmosphere. Independent of sunlight, the evolving ocean crust supports life in unique seafloor and subseafloor habitats that may resemble Earth's earliest ecosystems. From its formation until its return to the mantle by subduction, the evolving oceanic lithosphere interacts with seawater, sequesters water and other materials, and ultimately recycles them back into the mantle.

Mission Moho is the culmination of a four-decade quest by IODP (the Integrated Ocean Drilling Program, www.iodp.org) and its predecessors (ODP, DSDP) to increase our understanding of the oceanic lithosphere through deep scientific drilling. The Moho (Mohorovičić Discontinuity) is a seismically imaged, first order acoustic interface assumed to represent the transition between the Earth's crust and the underlying mantle. To date, this elusive frontier has been a symbolic goal for many geologists, but beyond the reach of available technology. With the recent commissioning of IODP's new riser-drilling vessel, D/V Chikyu, the technically challenging goal of drilling to and through the Moho has become feasible.

Mission Moho

The definition, by consensus, of the major components of an operationally realistic Mission Moho is the main community achievement of the workshop.

Documenting and understanding the evolution of more than half of earth's surface is an enormous and complex task, that could productively consume the resources of the IODP program for considerably more than a decade. Despite this complexity, and the diversity of individual scientific opinions and priorities, participants agreed, by consensus, on the core components of an operationally realistic Mission Moho. Given the complexity and scope of the problem, the achievement of this consensus is a remarkable community achievement.

The Mission Moho workshop was convened to provide guidance to IODP on the scientific and operational framework of a "Mission Moho". The principal workshop goals were to redefine the scientific objectives and to put forward the elements of a global strategy for an incremental increase in our understanding of the processes that drive the formation and evolution of the oceanic lithosphere.

The first priority is to drill a deep, full crustal penetration hole through the Moho, and into the uppermost mantle at a single site. Mission Moho planning must focus on achieving this goal as soon as feasible, because the road to the Moho will be a long one. The focus will be on progressively deeper and more technically challenging drill holes that will probe and sample the ocean crust, while providing the technological development and operational experience essential for the ultimate success of the mission.

Drilling and sampling a complete crustal section will enable us to: accurately estimate the bulk composition of the crust; understand the extent and intensity of hydrothermal exchange between the ocean crust and seawater; establish the chemical connections between the lavas that erupt at the seafloor and the melts that leave the mantle; more accurately estimate the chemical flux returned to the mantle by subduction; test competing models of lower crustal magmatic accretion; calibrate regional seismic measurements and the layered-crust models derived from them; better understand the origin of magnetic anomalies; and determine cooling rates of the lithosphere. By sampling across the crust-mantle boundary we will, *for the first time,* be able to: define, at least in one place, the geological meaning of the Mohorovičić discontinuity; determine the *in situ* composition of the uppermost mantle and its deformation; and address details of the physics and chemistry of mantle melt migration.

There was a clear consensus that this first full-penetration hole should be in fast-spread ocean crust. Although only 20% of the modern mid-ocean ridge system is fast-spreading (>80 mm/yr), more than 50% of present day ocean crust (representing 30% of the Earth's surface), and an even higher proportion of the crust that has been subducted back into the mantle during the last 200 Ma, was created at fast spreading ridges. Ocean crust produced at fast spreading ridges appears to be uniformly layered and relatively homogeneous, reflecting a relatively uniform, hence simpler to understand mode of accretion. We already have well developed theoretical models encompassing several possible styles of magmatic accretion at fast spreading ridges. An understanding of accretion processes based on one site might therefore reasonably be extrapolated to describe a significant portion of the Earth's surface.

Workshop participants also agreed that complementary studies of slow-spread lithosphere will be essential to fully understand the architecture of the ocean crust. Studies that explore crustal structure and the nature of the Moho in slow-spread lithosphere will supplement the vision that we gain from fast-spread crust. Wherever it has been studied, slow-spread crust is laterally heterogeneous, often on a relatively small scale (hundreds of meters). Crustal sections often include fault-emplaced, serpentinized peridotites of mantle origin. Despite this complexity, the (seismically-defined) Moho is usually well defined. Current hypotheses are that the Moho in slow-spread environments is: 1) the boundary between residual (after melting) upper mantle rocks and an intrusive igneous crust, 2) a broader zone of inter-layered ultramafic and mafic rocks, 3) an alteration front caused by deep penetration of water (serpentinization), or any combination of these three. Carefully targeted deep drilling is needed to assess these hypotheses and related questions, including the role of serpentinization in modifying seismic signatures, and especially in the transition from "crustal" to the higher "mantle" seismic velocities of around 8 km/s. The extent to which existing or planned drilling projects in slow-spread crust should be included in a Mission Moho was not resolved at the workshop. Criteria for inclusion of such projects will have to be defined by a mission proponent team.

Penetrating the entire ocean crust will require riser drilling technology. The world's only scientific riser drilling vessel "Chikyu" ("Earth" in Japanese; www.jamstec.go.jp/chikyu/eng) is scheduled to start operations for IODP in September 2007. For eventual penetration of the fast-spread oceanic crust, a technically challenging modification of the riser from the current 2500-meter maximum depth to at least 4000 meters (preferably 4500 meters) will be required. The construction of such a deep-water riser capability was recently included as one of five domestic science and technology high priorities by the Japanese Government. Even with this depth capability being available sometime after 2010, the journey to Moho will be long. The number of potential deep drilling sites, on fast-spread seafloor that is old enough, and therefore cold enough (>15 million years) but still shallow enough for riser capability is limited. It is imperative that any site chosen for a deep penetration hole is thoroughly investigated and characterized geophysically, geologically, geochemically and petrologically. Boreholes are spatially limited, and they need to be understood in their broader context. Spatial context for ODP and IODP drill holes is primarily provided before and after drilling occurs through appropriate site surveys, and can be complemented by field studies in ophiolites, and by drilling in tectonic windows that provide direct access to the lower crust and rocks that once formed the uppermost mantle. These windows of opportunity provide important short cuts to test models of lower crustal accretion, hydrothermal alteration and physical properties. The knowledge thus gained will enable model refinements and better experimental designs for progressively deeper penetration of intact oceanic crust.

INTRODUCTION

The formation and evolution of the oceanic lithosphere is the dominant process in the chemical differentiation and physical evolution of our planet. This evolution encompasses the transfer and transformation of material and energy from Earth's mantle to the crust and from the crust, to the ocean and atmosphere. Independent of sunlight, the evolving ocean crust supports life in unique subsurface and seafloor habitats that may resemble the earliest of Earth's ecosystems. From its formation until it returns by subduction to the mantle, the oceanic lithosphere interacts with seawater, sequesters surface materials (including water) and recycles them back into the mantle. The potential for IODP to contribute to an improved understanding of the composition, structure, and evolution of the ocean lithosphere is enormous and has been enunciated in planning documents since scientific ocean drilling began.

IODP is unique in its ability to provide effective tools for direct scientific sampling and measurement in remote and hostile deep sub-seafloor environments. IODP platforms are the only tools readily available for the collection of physical and chemical data, and for direct sampling of fluids, igneous rock, consolidated sediment, fluids and microorganisms below the seafloor in the deep ocean basins.

Since the end of the 60's, scientific ocean drilling programs (DSDP, ODP and IODP) have drilled and cored series of holes in oceanic basement (Figure 1). These led to major improvements in our understanding of the ocean crust architecture and of mid-ocean ridge processes, that have been recently outlined in two summary articles (Dick et al., in press; Ildefonse et al., in press). Although the number of deep basement holes is limited, IODP's most recent successes in this arena are two deep holes at complementary sites. Hole U1309D, in slow-spread Atlantic Ocean crust, reached 1415 m below sea floor and recovered a complex series of gabbroic rocks (Blackman, Ildefonse, John, Ohara, Miller, MacLeod et al., 2006). Hole 1256D, in superfast-spread crust of the eastern Pacific Ocean, reached 1507 m below seafloor and, for the first time, passed through a complete Layer 2 (pillow basalt and sheeted dike) sequence, into the transition between sheeted dikes and underlying gabbros (Wilson et al., 2006). Considerable experience about drilling deep in the ocean crust was gained with these two holes, and with earlier deep ODP Holes 504B and 735B. Holes 1256D and U1309D remain open and are ready to be deepened in coming years. For these and similar crustal drill holes to penetrate to significantly greater depths (beyond a few hundred additional meters), parallel development of appropriate technology and operational experience is essential.

The Mission Moho workshop was convened to provide an opportunity for interested scientists to redefine the scientific goals and objectives for deep crustal drilling, to propose elements of a global strategy, and to develop community priorities in pursuit of IODP's 21st Century Mohole Initiative "to advance significantly our understanding of the processes governing the formation and evolution of oceanic crust". In particular, the workshop focused on development of a scientific and operational framework that can guide an IODP Mission Moho for a decade or more. An important part of this framework is to define a "Road to the Moho" by identifying the scientific and engineering objectives that can be addressed immediately, with available technology, while leading us toward the ultimate "Mohole" -- a complete *in situ* section through the ocean crust.

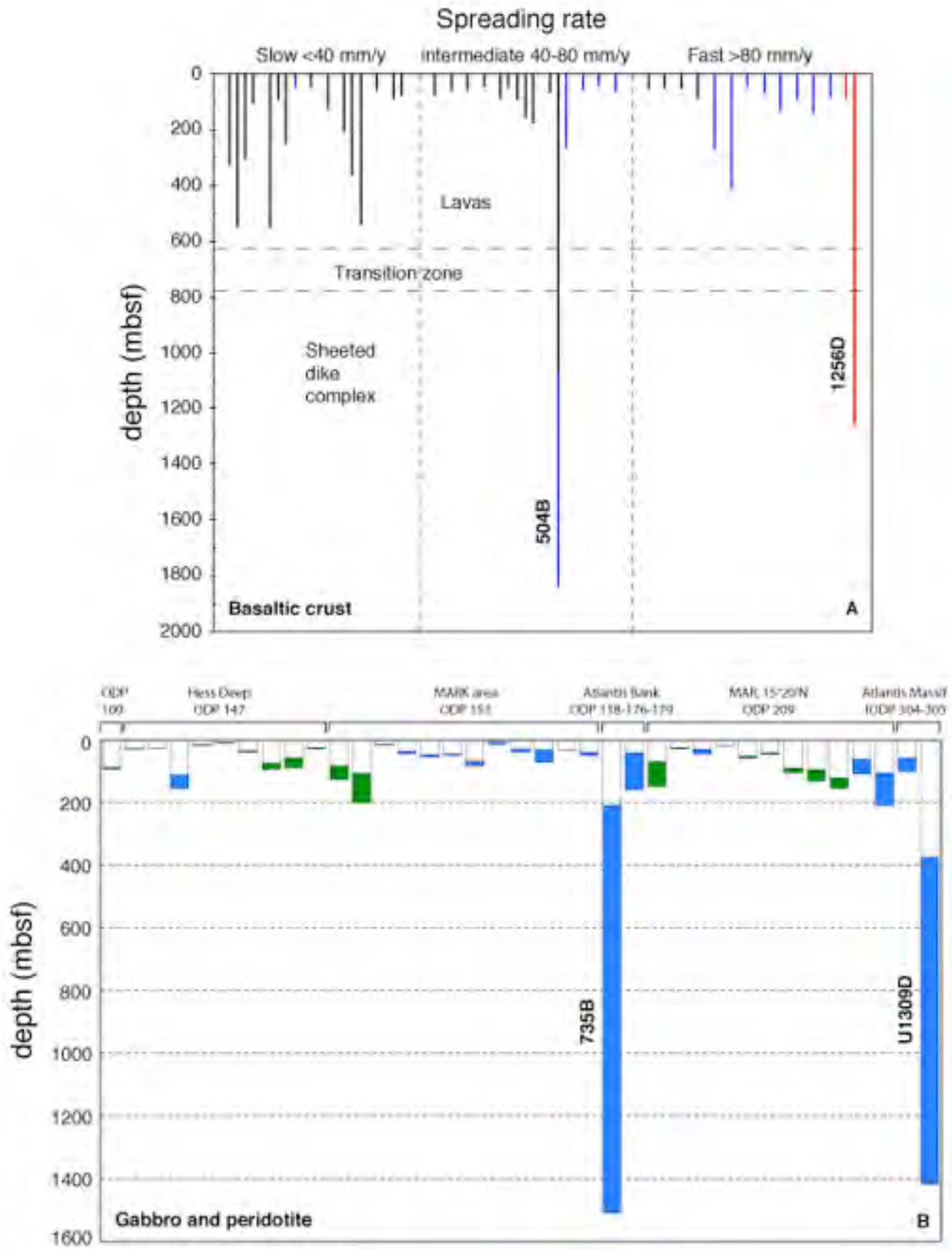


Fig. 1 - Scientific boreholes in oceanic crustal and mantle rocks. A) Depth of penetration of holes (deeper than 50 meters below seafloor) into basaltic basement, as a function of spreading rate. The boundaries between erupted lavas, the dike–lava transition zone, and the sheeted dike complex are placed at arbitrary depths based on Hole 504B stratigraphy. Black = DSDP holes, blue = ODP holes, red = IODP holes. Modified from IODP Expeditions 309 and 312 scientists (2006). B) Depth of penetration of all ODP and IODP holes (deeper than 10 meters below seafloor) into gabbroic rocks or residual mantle peridotite. Blue = dominantly gabbro, green = dominantly peridotite, white = no recovery. Modified from Blackman et al. (2006).

THE ROAD TO THE MOHO -- SCIENTIFIC GOALS AND OBJECTIVES

Scientific Goals for Deep Penetration Holes

Scientific Goals of Deep Drilling

The process of drilling a suite of increasingly deep holes, with the ultimate goal of full-crustal penetration, fulfils a diverse set of scientific goals. These are ordered in scope from general to more specific and in depth from the shallow crust to the mantle

- Quantifying and understanding the flux of mass and heat between the mantle, crust and hydrosphere
- Establishing the bulk composition of oceanic crust
- Understanding the magmatic and tectonic processes that form oceanic crust
- Determining the alteration, thermal, and fluid-flow history of the crust
- Characterizing the geologic nature of the (seismic) Moho and its variability
- Understanding the variation in rheological properties and state of stress through the oceanic lithosphere
- Obtaining a sample of pristine oceanic mantle and constraining the composition of primary mantle melts
- Determining the composition and deformation history of the uppermost mantle and its variability
- Relating composition and deformation history of the lithosphere to seismic properties and seismic boundaries
- Characterizing the variability of mantle flow, melt transport and crustal formation processes as a function of different magmatic and tectonic settings

In planning to fulfill these goals, it must be recognized that "both the journey and destination" are important. Each of the site surveys that are essential to establish three-dimensional context for candidate Moho drill sites, and each of the progressively deeper and more challenging drill holes that are essential for developing technical and operational expertise, will have its own unique scientific objectives and will make its own scientific contribution.

Deep drilling objectives

In order to achieve the scientific goals, a number of operational objectives can be expressed in scientific terms. As for the science goals, the objectives for a broadly-envisioned Mission Moho provide the means to address a variety of issues, including crustal accretion processes, global variability of crustal architecture, and characterization of the Moho and underlying mantle. These objectives include:

- To characterize at least one primary site and one alternate through thorough geophysical and geological site surveys.
- To characterize the same sites through a series of increasingly deeper and more challenging drilling programs.

- To achieve total penetration of oceanic crust and uppermost mantle in a single hole in at least one location.
- To achieve multiple penetrations of the dike-gabbro transition, the lower crust, and the crust/mantle transition at complementary sites characterized by different magmatic and tectonic settings.

Collectively, these operational objectives will address two key scientific objectives:

- To characterize lateral variability of the ocean lithosphere (i.e. variability of accretion processes) on scales from global down to a few tens of meters at a single site
- To determine the lithologic character of the well known crustal seismic transitions and the extent to which seismic and lithologic transitions are correlated.

Strategies and Priorities for Deep Drilling

In planning for Mission Moho, the following broad guidelines should be considered:

- To achieve a Mission Moho requires a commitment to a ~ 10-year program of increasing complexity.
- Mission Moho will occupy multiple sites (4-6), including at least one primary and one alternate site as well as several complementary sites. Most sites will require multiple expeditions (12-20 total).
- A 4000+ meter riser will be required for the second half of the 10 yr mission.

If the riser can be engineered for 4500 meter water depth, the range of possible sites is significantly increased. Whether this is achievable must be known early in the mission to allow for final selection of a deep penetration site.

Recommended Components of Mission Moho

Complete Crustal Penetration – Primary Site

The primary site should be in fast spreading crust to take advantage of the reduced crustal thickness, simpler crustal structure, representative character of this tectonic setting. A few years ago, Site 1256 (Fig. 2) was chosen to initiate a deep hole in fast-spread crust, starting with ODP Leg 206, because it best meets a majority of the criteria for a deep penetration site (See "Lithosphere accreted at fast-spreading ridge", and "Keynote presentation on the outcomes of the ODP Architecture of the Lithosphere PPG") and currently has an open, deep hole into the uppermost lower crust. It is recommended that:

- Site 1256 be deepened as far as possible into lower crust using riserless technology.
- Design work begins as soon as possible for a deep, cased hole at Site 1256 that is engineered for riser drilling through the full crust.
- Site survey and other work begin as soon as possible to identify and characterize an alternative complete crustal penetration site. Such a site will complement Site 1256 and be available should adverse conditions be encountered. The alternate site should be in older, cooler crust.

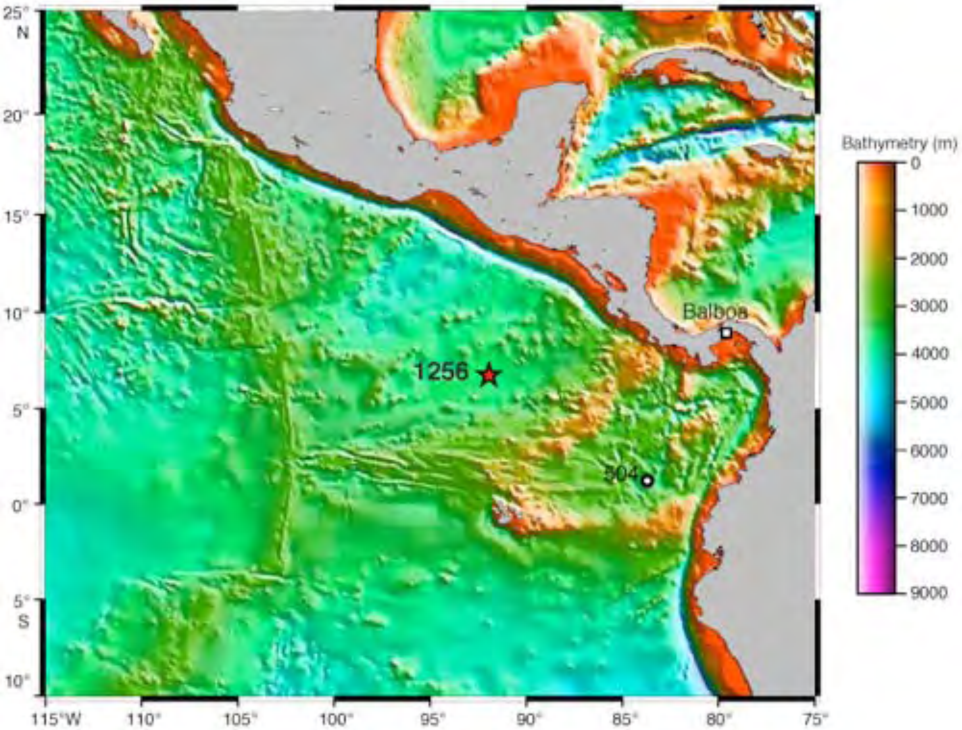


Fig. 2 – location of site 1256, Cocos plate, East Pacific (modified from Wilson et al., 2003)

Complementary Drilling to Sample Critical Crustal Boundaries

Non-riser drilling is required to characterize critical crustal boundaries that have been brought close to the seafloor by tectonic processes. Such drilling should build on knowledge and experience from a number of existing sites.

- For fast-spread crust, Hess Deep is the best known candidate site and the most readily accessible.
- For slower-spread crust a variety of options exist and a process must be developed by which the community can agree to prioritize these. One high priority site is Site U1309 on Atlantis Massif, where Hole U1309D is open to 1415 mbsf and should be deepened to gain experience in high temperature gabbro (and possibly peridotite) drilling. Drilling should also be considered on other core complexes, of which Atlantis Bank and the MARK area are well surveyed, and perhaps the best known.

Science Objectives for Fast-spread Lithosphere

The overarching goal for deep drilling in lithosphere generated at fast spreading rates is to progress as efficiently as possible toward full penetration of the ocean crust. Important, but subsidiary objectives are to effectively characterize three dimensional spatial variability in crust and mantle architecture and to document the processes and effects of crustal aging. For Mission Moho, objectives related to these subsidiary goals are necessarily limited to those that have direct relevance to the selection and characterization of a single deep drill site.

To achieve this goal will require drilling and related activities at a limited number of sites that can be divided into three site types: a primary deep penetration site, one or more back-up, deep penetration sites, and complementary sites. Key drilling objectives include:

- Designation of Site 1256 as the current primary site. This implies a commitment to work towards complete penetration through the gabbro of the lower crust into rocks that have mantle seismic velocities AND into peridotitic residues of partial melting. Ongoing scientific drilling, which must be coordinated and combined with significant technical development and feasibility testing, will also support a number of ancillary science goals. Activities at the designated site should include:
  - Deepening of Hole 1256D into presumed Layer 3 gabbro to the point where further riserless drilling is technically not feasible.
  - Additional drilling, to establish spatial context including primary and secondary shallow crustal variability, permeability and other characteristics.
  - Technical and engineering development, including drilling of an engineered, cased hole designed to become the ultimate deep hole.
  - Enhanced site survey activities including, but not necessarily limited to, high resolution deep seismic studies

- Identification and evaluation of potential backup sites, in case conditions at Site 1256 prove to be unsatisfactory for full crustal penetration. The greatest currently perceived threat at Site 1256 is from potentially high down-hole temperatures. For this reason, the alternate site should be on older crust. A critical limiting factor is that the site must be within reach of the planned deep riser for D/V Chikyu. This limit is currently 4000 meters. If the design target for the riser could be increased to 4500 meters, the number of potential sites would be significantly higher. Initial evaluations might encompass two or even three sites, with a relatively rapid narrowing to a single site for the more intensive investigations. Activities at such sites might include:
  - Site survey activities including seafloor mapping, heat flow, and seismic studies to determine both sediment thickness and seismic structure.
  - Initial shallow drilling to determine the nature of the upper crust and its potential to maintain a stable hole during extended deep drilling operations.
  - Deeper drilling, ideally at least to the dike-gabbro transition.

- Continued characterization of uplifted lower crustal and mantle material in the vicinity of Hess Deep. This is the only non-remote "tectonic window" in fast-spread lithosphere. It provides an opportunity to investigate both upper and lower crustal gabbros as well as altered upper mantle peridotite. Activities at Hess Deep might include:
  - Enhanced site survey activities to obtain a better three-dimensional structural characterization of the region
  - "Shallow" (a few hundred meters?) drilling targeted on intra-crustal and/or crust-mantle transitions

Each of these recommended activities is designed to build a knowledge base that will enhance our ability to design and execute an ultra-deep drill hole. Partly by design and partly by good fortune, however, these activities potentially serve a number of additional, important science objectives. Mission Moho planning activities should consistently seek to maximize these ancillary science goals. Site characterization activities, including the drilling of multiple short holes (around a planned or potential ultra-deep hole) will help to document both the small (sub-kilometer) scale variability of volcanic processes and their influence on hydrothermal circulation, crustal aging and geochemical exchange with the oceans. In addition, closely spaced holes provide opportunities for well-to-well hydrologic and geophysical studies.

In addition to igneous studies, further drilling in Hess Deep will allow better quantification of crustal alteration and aging processes, and the extent to which they can affect the lower crust, and the uppermost mantle. By focusing on transition zones, Hess deep drilling will also contribute to a better understanding of the relationships between seismic and lithological transitions in the crust.

Hydrothermal alteration studies are important wherever we drill in ocean crust. Hydrothermal fluid circulation changes the chemical composition and physical properties of the crust (and possibly, mantle), and these reactions constitute the principal linkages between lithospheric processes and the wider Earth system. In particular, the search for, and evaluation of, back-up sites will involve drilling in 40-60 Ma crust allowing the chemical and physical maturation of upper ocean crust in the previously unexplored middle age-range, to be much better quantified. This will, in turn, improve estimates of the impact of hydrothermal exchange on global chemical cycles including the composition of seawater and the crustal inputs to the mantle in subduction zones.

Science Objectives for slow and ultra-slow spread lithosphere

The overarching goals of deep crustal drilling in lithosphere generated at slower spreading rates are to efficiently characterize the spatial and temporal variability in crustal and upper mantle architecture, and to identify and constrain the key forcing functions that control this variability.

To achieve these goals will require drilling to various depths at a limited number of sites that encompass much of the known vertical and lateral variability of slow-spread crust.

Key objectives for this type of drilling include:

- Determining the lithologic nature of the (seismic) Moho in places where it is accessible by relatively shallow drilling.
- Investigating the contrast between crust formed along magmatically robust parts of slow spreading ridges (segment centers) and lava-poor segment ends. Is crust from segment centers similar in structure to fast-spread crust?
- Investigating the composition of, and deformation in the upper mantle by sampling fresh peridotite.
- Understanding the relationships between crustal architecture and tectonic setting.
- Determining the mineralogical origins of seafloor magnetic anomalies, and the nature of polarity transitions in heterogeneous, slow-spread crust.
- Determining the depth to which seawater penetrates in different tectonic settings. Is there a relationship between crustal architecture and depth of seawater penetration?

- Investigating the chemical, mineralogical and microbiological character and variability of hydrothermal systems.

Because of the inherent variability of slow-spread lithosphere, a truly comprehensive program to achieve these objectives would require far greater resources than IODP can provide. Thus, there is a clear need for prioritization, both among the wide variety of explicitly slow-spread objectives and potential sites, and between slow-spread and fast-spread objectives. To achieve consensus on priorities among explicitly slow-spread objectives will require a carefully prepared and explicitly focused process. This was not, and could not have been achieved at the Mission Moho Workshop. Workshop participants did, however, reach a very clear consensus, that Mission Moho should focus on the ultimate goal of achieving full crustal penetration at a single fast-spread site. There was also strong agreement that lessons to be learned, both technologically and scientifically, on the way to this ultimate goal may include slow-spread crust objectives.

WORKSHOP PROCEEDINGS

BREAKOUT GROUP REPORTS

Introduction

The Mission Moho workshop alternated plenary sessions with smaller breakout activities (see "workshop agenda"). There were a limited number of keynote talks (see "Keynote Presentations") and reports on recent activities, and an evening poster session (see "Extended Abstracts of Poster Presentations").

One of the key tasks for the workshop participants was to identify, from among a plethora of scientific ideas, questions and priorities concerning the origin and evolution of the ocean lithosphere, a compelling, coherent and operationally feasible subset.

To accomplish this task, it was essential for the breakout groups to explore a range of scientific goals and priorities that is much broader than the possible scope of any single IODP Mission. Many of these goals are, and will remain important, both in their own right and because they will provide the broader context within which Mission Moho must be understood. They should be pursued to the maximum extent possible, either inside of or outside of, but often complementary to, Mission Moho. In the following sections, the full breadth of the breakout discussions is recorded as faithfully as possible.

A note on Microbiological Objectives

The reports from the breakout groups do not fully include microbiological objectives. This reflects the very small number of participants with appropriate expertise – a major IODP microbiology workshop was scheduled only two weeks later. Workshop participants do, however, recognize the importance of this field and the microbiological studies must be advanced in conjunction with the pursuit of lithospheric goals.

Formation and architecture of the ocean crust

Chairpersons: Bob Detrick & Chris MacLeod

This group focused generally on Science Goals and Objectives for deep holes into the oceanic crust and uppermost mantle, then followed with a discussion of Strategies, including some of the technological aspects raised by Mission Moho. Members of the expert engineering panel contributed to the latter discussion.

Scientific Goals for Deep Penetration Holes

On the "Road to the Moho", BOTH the journey and destination are important

The following list distills the range of goals relevant for Mission Moho, as envisioned broadly in this early session. The order is from general to more specific, from crust through to mantle.

- Quantifying and understanding the flux of mass and heat between the mantle, crust and hydrosphere.
- Establishing the bulk composition of oceanic crust.
- Understanding the magmatic and tectonic processes that form the oceanic crust.
- Determining the alteration, thermal, and fluid-flow history of the crust.
- Characterizing the geologic nature of the Moho and other seismic and lithologic transitions, and their lateral variability on a variety of scales.
- Understanding the rheological properties and state of stress of the oceanic lithosphere.
- Obtaining a sample of *in situ* oceanic mantle and constraining the composition of primary mantle melts.
- Determining the composition and deformation history of the uppermost mantle and its variability; relating these to seismic properties of uppermost mantle.
- Characterize how the processes of mantle flow, melt transport and crustal formation vary as a function of different magmatic and tectonic settings.

Objectives for Deep Penetration Holes

Operational objectives that will accomplish the goals of a broadly-envisioned Mission Moho should address crustal accretion processes, document crustal architecture in representative settings, and characterize the Moho and underlying mantle. They include:

- Drilling through the entire oceanic crust and into the uppermost mantle in at least one location.
- Drilling through accessible dike-gabbro and crust/mantle transitions in different magmatic and tectonic settings.
- Drilling accessible lower crustal sections.

Technical Issues for Deep Penetration Holes

A joint scientific-technical session discussed technological issues that might affect the strategy or outcome for Mission Moho. The issues discussed included:

(1) What are the limits of riserless drilling?

- The maximum contribution to Moho drilling that can be expected for riserless technology would be a (approximately) 3 km hole that is cased and ready to deepen using riser system.
- Currently planned drill string limits are approximately 8000m for IODP's riserless vessel, and approximately 10000m for Chikyu. Longer drill strings may be possible using other alloys and/or other string configurations.

(2) What are the limits of scientific riser drilling? Current plans for Chikyu call for development of a 4000 meter riser as soon as possible. If this can be extended to 4500 meters the range of potential sites available to Mission Moho would be significantly increased.

(3) More experience is needed in drilling high temperature conditions, especially to understand the effects of thermal stress on hole stability in ocean crust lithologies. The temperature/cost limits, beyond which we are unlikely to successfully drill, are currently unknown. They will need to be established through the experience of drilling progressively deeper holes.

(4) Temperature limits for existing logging are probably 250-275°C, but more experience, within IODP, is required.

(5) The extent to which recovered samples are "representative" of the drilled interval is variable and subject to question. Careful attention must be paid to this issue as experience is gained. Increased recovery may increase confidence in the representative nature of recovered core. If, however, increased recovery requires increased drilling time (slower penetration rates), the trade-off between better recovery and reduced hole depth must be carefully evaluated.

(6) The long-standing need for accurate core orientation to facilitate structural and magnetic studies was reiterated.

(7) The well-known difficulty of starting holes in rubbly basalts and of obtaining samples from the upper 50-100 meters of the ocean crust is a long-standing problem for scientific drilling and for our overall understanding of crustal evolution. In particular, the presence of rubbly basalts could impede the establishment of a deep penetration hole at some sites. The sampling problem may be best addressed by use of a different tool/platform (for example, the BGS seafloor drill). The problem of starting a deep hole in rubbly terrain requires further technological development, perhaps including modifications to the bottom-hole assembly, continued development of hammer-drilling and/or drill-in casing, and others.

Strategies and Priorities for Deep Drilling

Strategy discussions were based on a general agreement that deep drilling objectives should be pursued, at least at first, by continuing work at Site 1256. The discussion was incomplete and no formal consensus was reached. Issues to be considered as deep drilling strategies are developed include:

Boundary conditions for Mission Moho:

- Timeframe 10-15 yrs; beginning in 2009.
- 4-6 "components", each potentially consisting of multiple expeditions.
- 12-20 expeditions over this period
- 4000 meter (or perhaps, 4500 m) riser will be available in the second half of the 10 yr mission

Strategies for Complete Crustal Penetration Hole in Fast Spreading Crust

- Deepen Site 1256 as far as possible into lower crust using riserless technology.
- Drill and case a riserless hole to prepare for riser drilling through the full crust. This should be at Site 1256, or at an approved alternate site identified in the interim.
- Design and initiate, as soon as possible, a riser drilling strategy for complete crustal penetration at an approved site. Depending on progress toward site approval, planning might be required for one or two alternate sites. A minimum strategy would include a shallow (2km) hole designed to recover the upper crust, and a nearby hole that is drilled (not cored) to the depth of the first hole, cased to an appropriate depth for upper hole stability, then drilled and cored to Moho using a riser for well control.

Strategies for Offset Drilling to Sample Critical Crustal Boundaries – Fast-spreading Crust

- Focus on Hess Deep as the only accessible fast-spread site.
- No special technical requirements.

Strategies for Offset Drilling to Sample Critical Crustal Boundaries – Slow-spread Crust.

- Deepen Hole 1309D (Atlantis Massif) to gain immediate experience in high temperature gabbro and peridotite drilling.
- Initiate a community-based process to set priorities for drilling at other sites of opportunity, such as other core complexes in the Atlantic, and Atlantis Bank on the Southwest Indian Ridge.

General Strategies

- Participants recognized that lessons can and should be learned from other programs, including deep continental scientific drilling, Iceland geothermal drilling, and industry.
- A number of participants suggested that continuous coring in deep holes may be too slow to allow for satisfactory depth advances in real time. The more time taken for drilling, the higher the risk of hole failure due to thermal stress or other problems. Slow coring may also be at odds with a "reasonable" timetable. This implies that some intervals might be drilled without coring. Spot cores would be taken at discrete intervals, and riser technology would make drill cuttings available at the drill floor. Others argued that continuous coring is highly desirable if the science objectives are to be maximized. This is an important issue that must be considered as experience is gained.

Lithosphere accreted at fast-spreading ridges

Chairpersons: Damon Teagle & Robert Zierenberg

Although only 20% of modern ridges are currently fast-spreading (>80 mm/yr), more than 50% of the present day ocean crust (~30% of Earth's surface), and the great majority of crust subducted back into the mantle during the last 200 Ma, was produced by fast spreading. Available data suggest that fast-spread ocean crust is more uniform than slow-spread crust, and more closely matches the simple layered "Penrose" model developed from ophiolites. For these reasons, an understanding of accretion processes at one site might reasonably be extrapolated to a significant portion of Earth's surface. Importantly, we already have well developed theoretical models of competing styles of magmatic accretion in fast spreading ridges and methods have been proposed to test these model using samples recovered from drilled sections of ocean basement together with complementary studies of ophiolites, in particular the Oman ophiolite.

Priorities for Fast Spreading Crust

Within this group, there was broad consensus for three main objectives:

- Full penetration of the ocean crust.
- Spatial variability of the ocean crust.
- Temporal variability (aging) of the ocean crust.

Full penetration of the oceanic crust was agreed to have the highest priority, but there was no attempt to reach a consensus on the priority of the other two objectives. A variety of strategies were discussed and are summarized below. All are scientifically important for an understanding of the ocean lithosphere, but not all are necessarily priorities for Mission Moho.

The highest priority is for activities that directly support the goal of complete penetration of fast-spread ocean crust: from the shallowest lavas, through the dike and gabbro sections, into both the region of mantle seismic velocities and peridotites that are residues of partial melting (as opposed to cumulates formed by crystallization from melts). A complete section will address key scientific problems that, after nearly 50 years, have finally become feasible with the commissioning of *D/V Chikyu*. By drilling a complete section through the ocean crust, we will, for the first time be able to use *in situ* samples and data to:

- Estimate the bulk composition of the crust,
- Establish the chemical connections between seafloor lavas, the intrusives directly beneath them, and the underlying mantle,
- Develop and evaluate models of lower crustal magmatic accretion processes based on structural and mineralogical data,
- Quantify the extent and intensity of hydrothermal exchange between the ocean crust and seawater,
- Calibrate regional seismic measurements with lithological data,
- Understand the origin of magnetic anomalies,
- Improve estimates of the chemical fluxes returned to the mantle by the subduction of the oceanic lithosphere,
- Determine the geological meaning of the Mohorovičić Discontinuity,

- Address fundamental questions about the nature of melt migration in the mantle, mantle deformation, lithospheric cooling rates and the composition of the uppermost mantle.

A Mission Moho strategy should center on the deep drilling of at least one intact section of ocean crust complemented by the exploitation of tectonic windows of opportunity (e.g., Hess Deep) that provide direct access to rocks that once formed the lower crust and/or the uppermost mantle. These windows of opportunity provide important short cuts to test models of lower crustal accretion, hydrothermal alteration and physical properties. They provide additional knowledge that can be used to refine models and design better experiments to complement and enhance the science goals of the deep penetration site. Also imperative for our understanding of crustal and mantle processes and the ongoing design of a full crustal penetration hole, is a thorough geological and geophysical characterization of each target site. This should include deep seismic experiments to characterize the Moho and constrain deep crustal and upper mantle properties. These experiments must be far more ambitious and comprehensive than current IODP site surveys.

Towards a Full Penetration of the Ocean Crust

Deep drilling at Site 1256 – Eastern Equatorial Pacific

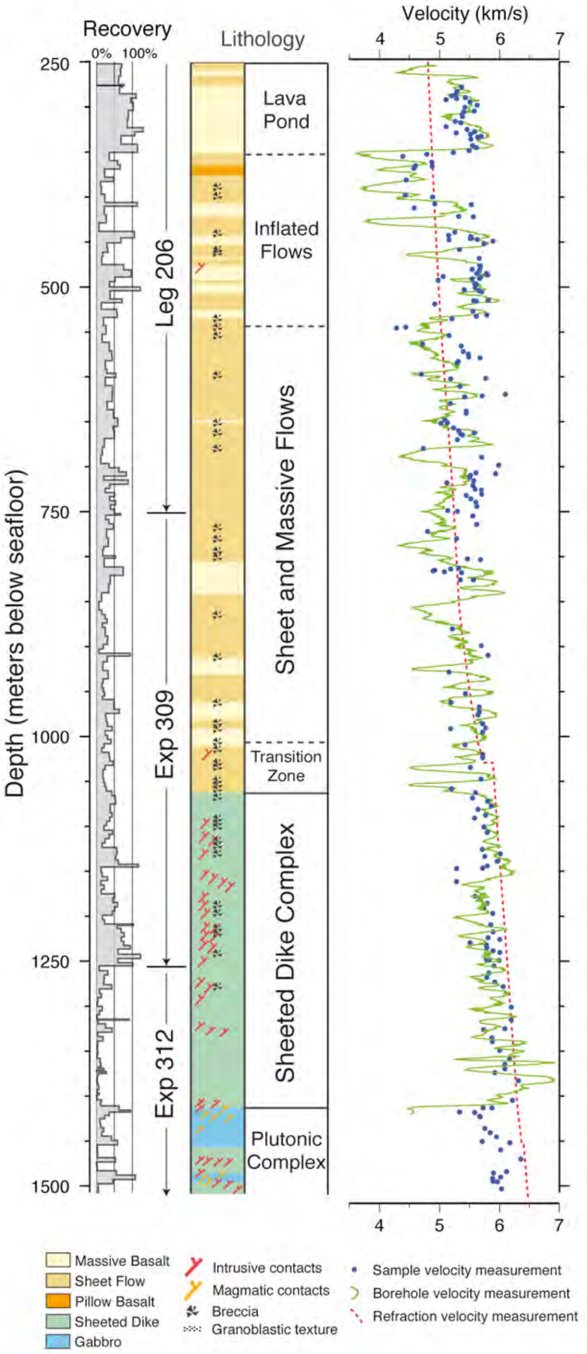
Because drilling young ocean crust is technically extremely challenging, building on recent success and enhancing operational experience by deepening Hole 1256D should be the highest short-term priority for “the road to the Moho”. The selection strategy for Site 1256 was to target a region of ocean basement where the dike-gabbro transition was predicted to be at its shallowest depth within the crust. Hole 1256D was designed for deep drilling, based on information from initial pilot holes at the site, by emplacing sixteen-inch casing into the uppermost basement with 16-in casing. Initially, during ODP Leg 206, the hole was deepened beyond the casing to 502 m sub-basement (msb). IODP Expeditions 309 & 312 continued coring to 1255 msb, intersecting gabbro at 1157 msb. Hole 1256D is the first to pass from dikes to gabbros, and the first to sample gabbro from intact, layered oceanic crust (Wilson et al., 2006). However, with only 100 m of gabbro sampled, key hypotheses about the accretion of the ocean crust remain to be tested.

Hole 1256D was left clear of debris and open to its full depth, providing an immediate opportunity for additional major scientific and technical achievements early in Phase II of IODP. IODP engineers have evaluated Hole 1256D as being in good condition and cautioned against attempts to install further casing. Their suggested hole deepening strategy utilizes very large mud-sweeps (100-150 bls) to clear of debris and remove cuttings from the hole. This strategy proved successful towards the end of Expedition 312. ODP and IODP experience suggests that drilling through gabbro will be less challenging than it was in the extremely hard, brittle lithologies of the lower sheeted dikes.

The strategy beyond Hole 1256D will depend on experience in the deepening phase. Should Hole 1256D fail early, and depending on the nature of the failure, the short term preferred strategy would be to start a new hole close to Hole 1256D and to drill as deep as possible with available (non-riser) technology. The hole design would be based on experience in Hole 1256D and would involve casing as deeply as required to stabilize the borehole walls and assist in the clearing of cuttings.

Hole 1256D

Hole 1256D is located in the eastern equatorial Pacific on 15 million-year-old crust that formed at a superfast spreading rate (see Wilson et al., 2003 for full site justification). This site was endorsed by the ODP "Architecture of the Oceanic Lithosphere Program Planning Group" (1998) as the optimum location to pursue major science goals in fast spreading rate crust, based on an apparent relationship between spreading rate and the depth to axial low velocity zones, thought to be magma chambers, imaged by seismic surveys of modern active ridges. The hole is currently rooted in a dike-gabbro transition zone and the gabbros so far sampled have compositions similar to the overlying lavas and dikes. Cumulate rocks have not yet been encountered and shipboard physical property measurements indicate that the core has P-wave velocities characteristic of seismic layer 2. Downhole measurements indicate that the current temperature at the bottom of Hole 1256D is ~115-125°C. A proposal to deepen Hole 1256D (IODP Proposal 522Full) is currently under consideration by the IODP Science Advisory Structure (SAS). The Moho is imaged at the site at 5.5 km depth.



Right: Summary of drilling results in Hole 1256D showing recovery, major lithologies, and seismic velocities measured on discrete samples, by wireline tools, and by seismic refraction (from Wilson et al., 2006).

Site 1256 appears at present to be the lead candidate site for a complete crustal penetration. An important concern, however, is its location on relatively young (15 Ma), hot ocean crust. High temperatures at depth may preclude deep drilling. *In situ* thermal gradients and gabbro thermal conductivities are not well known, but current best estimates suggest upper mantle temperatures in excess of 250°C. It is not yet known if such temperatures will cause problems during deep-riser drilling by *R/V Chikyu*. It should be noted that ODP Leg 169 operations in an active, sediment-hosted hydrothermal system did not encounter temperature problems until zones 274°C fluid were encountered. In Iceland, geothermal drilling is successful up to at least 350°C.

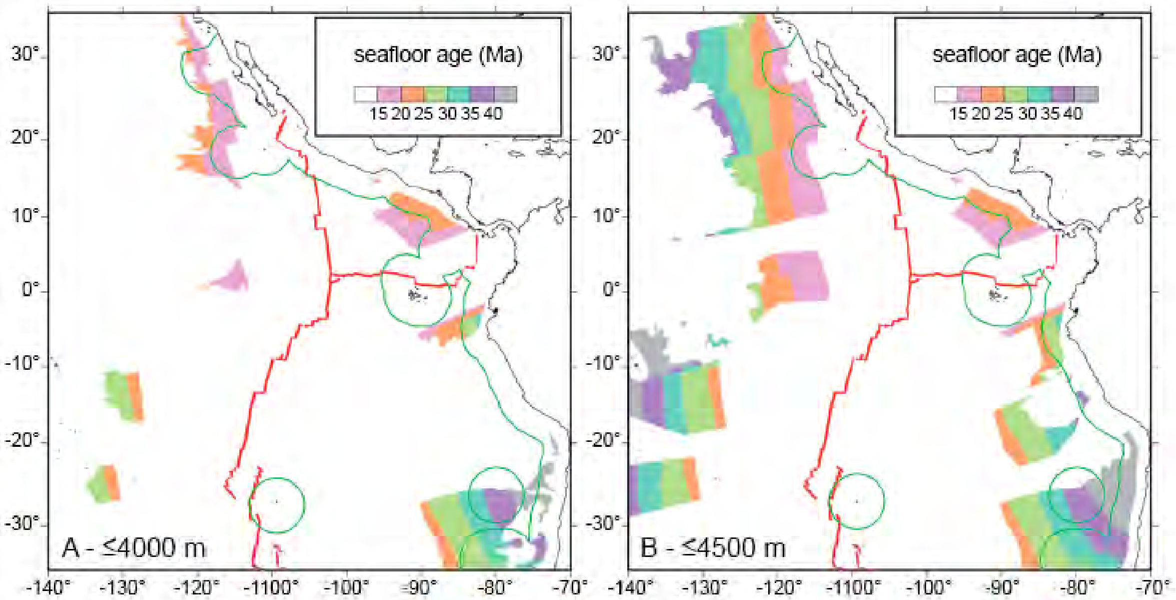
Alternate Sites

Scientific justification for extending the RV Chikyu riser capability to 4500 meters

Sites that satisfy the deep-drilling criteria listed in the previous section are extremely rare in water depths of 4000 meters or less. In fact, no site has been identified to date, and a 20 Ma site at 4000 meters depth would, in fact, be anomalously shallow. A longer riser would allow drilling in deeper water, which equates directly to drilling in older crust. This is very important because:

- Drilling in older crust means that the temperature at the crust-mantle boundary is lower (<200°C for crust older than ~20 Ma), decreasing the technical challenges and increasing the likelihood of success.
- Drilling in older crust will provide a longer time-integrated record of hydrothermal exchange between the oceans and the ocean crust. This would greatly enhance our ability to:
    - Quantify the chemical and physical evolution of the ocean crust,
    - Estimate the impact of hydrothermal exchange on global chemical cycles including the composition of seawater,
    - Estimate inputs to the mantle from subducted crust.
- Drilling in deeper water greatly increases the area of ocean floor available for conducting the Project Moho drilling, allowing more astute site selection and maximizing chances for success.

Below: Possible drilling areas for the Chikyu in the eastern Pacific, depending on the riser depth capability. Colored areas correspond to reasonably well mapped and tectonically simple crust, that is older than 15 Ma, and less than 4000 meters below sea level (A) or less than 4500 meters below sea level (B). Green lines delimitate Exclusive Economic Zones of countries that are not IODP members.



While operations are proceeding at Site 1256, significant efforts to develop one or more alternate sites should be undertaken. If the design target for the *R/V Chikyu* deep riser can be increased to 4500 m the number of potential target sites on Pacific fast spreading crust will be significantly larger.

A viable alternate site should have:

- Crustal age greater than ~20 Ma, implying mantle temperatures less than 200°C
- A well defined Moho at 5 to 5.5 km (in reach of a 10000 m drill string)
- Adequate sediment cover (>150 m) to support a re-entry cone and casing to basement.
- High spreading rate (correlated with thinner basalt layer)
- An original latitude of > ±15° to enhance magnetic studies
- Reasonable proximity to major port facilities
- A 12 months weather window.

Spatial Variability of Ocean Crust

It is well recognized that no single hole can adequately describe the variability of the ocean crust even for relatively uniform fast-spread crust. Full crustal drilling in one, or even a few locations must be complemented by shallower drilling, to document:

- The range of volcanic processes at mid-ocean ridges
- The effects of this variability on crustal aging and geochemical exchange with the oceans
- Lateral variability in the lower crust and uppermost mantle.

The group identified two important strategies for understanding spatial variability:

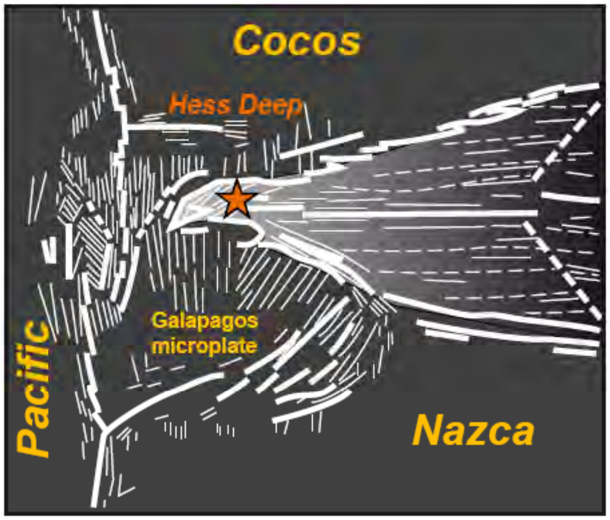
- Continued shallow drilling in tectonic windows to investigate the heterogeneity of the middle to lower crust and to understand the process of deep-seated magmatic accretion
- Continued shallow drilling of intact upper oceanic crust to establish initial volcanic and petrological variability and to investigate the role of shallow alteration processes in crustal evolution.

Accretion of the Lower Crust - shallow drilling in tectonic windows

Our understanding of accretion mechanisms for fast-spread lower oceanic crust is severely limited by our inability to access it directly, and by the limited number of accessible tectonic windows in fast-spread crust. Of the known examples, Hess Deep, Pito Deep, Endeavor Deep, and the Blanco Fracture Zone, Hess Deep is by far the best known. It was surveyed and sampled by numerous submersible campaigns (Francheteau et al., 1990; Karson et al., 1992; Karson et al., 2002), and drilled during ODP Leg 147 (Gillis et al., 1993).

Further drilling in Hess Deep, following thorough site characterization, will provide cores from the middle (upper gabbros) and lower crust and uppermost mantle, to form a composite section of the plutonic basement of fast spreading rate crust formed at the East Pacific Rise. Along-strike drilling will allow quantification of lateral variability at different crustal levels. Geochemical, textural and physical properties studies of these cores, linked to ophiolite observations, especially in Oman, will complement, and may be helpful in the design of, a future Mohole.

Hess Deep



The Hess Deep rift valley (2°N, 101°W), near the Galapagos microplate at the Pacific-Cocos-Nazca triple junction, is the only place on the Earth's surface where a substantial section of fast-spreading lower crust and shallow mantle is known. The Cocos-Nazca ridge is propagating westward at a rate comparable to the half spreading rate of the EPR (~65 mm/yr); hence young (~1Ma) lithosphere generated at the EPR is being rifted ahead of the advancing Cocos-Nazca ridge. Submersible studies have shown that a complete crustal section is exposed. Well studied sections of intact upper crust, from the upper gabbros to the lava sequence, are well exposed along the northern scarp bounding Hess Deep and reveal significant lateral variability in crustal structure and hydrothermal alteration (Francheteau et al., 1990; Karson et al. 1992; Karson et al., 2002). Plutonic and shallow mantle sequences, dismembered by the Cocos-Nazca rifting, are exposed on an intra-rift ridge and on a slope southward from it down to the axis of the Deep at ~5400 m water depth. Because of its unique exposure Hess Deep has been identified as the only feasible area for studying lower crust and mantle sequences in fast-spreading oceanic crust by drilling, and as a 'natural laboratory' of the highest priority for future investigations. An externally reviewed proposal for further drilling in Hess Deep (Proposal 551Full) currently resides within IODP SAS, awaiting further site survey information. A UK-funded expedition to undertake the required site survey is funded and provisionally scheduled on RRS James Cook in January 2008.

Variability of the Upper Crust

Chemical exchange between seawater and the oceanic crust occurs predominantly in the upper few hundred meters, although the extent of deep hydrothermal circulation off-axis remains unknown. The extent, intensity and duration of hydrothermal circulation must be strongly dependent on the volcanic stratigraphy, basement topography, sediment-cover, and crustal age, but the controls are presently unknown. Our knowledge of the relative importance of these processes is limited by the paucity of drill holes into intact upper oceanic crust. Also limited by the paucity of drill holes is our ability to infer the geological nature of even the upper oceanic crust from geophysical data. Drill holes, and especially pairs or arrays of shallow holes designed to ground-truth regional geophysical information would greatly enhance our ability to quantify the variability of the upper oceanic crust.

Here we encourage a strategy to characterize the upper oceanic crust, in the neighborhood of potential deep-drill sites, and at other sites of opportunity that variations in parameters such as seismic velocity, heat flow and basement topography. Multiple closely spaced drill holes will also allow for active hydrologic experiments, essential to establish key parameters such as permeability, and to and provide hosts for microbial and geochemical experiments and observatories.

Temporal variability – Aging of the Ocean Crust

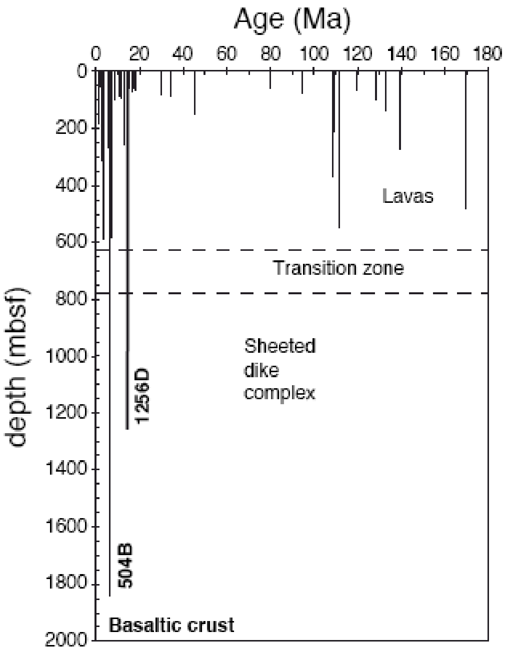
Penetration to Gabbro in Mature Ocean Crust (60-80 Ma?)

Hydrothermal alteration provides a critical link between the ocean lithosphere and the wider Earth system. Seawater-basement exchanges beneath mid-ocean ridges and on especially beneath the extensive ridge flanks dominate the oceanic chemical budgets of many key tracers (including ^{87}Sr, ^{18}O, K, Mg, Ca, U, CO_2). Similarly, subduction of altered ocean crust provides the dominant, ongoing chemical input to the mantle. Closure of veins and voids by secondary mineral precipitation increases seismic velocities, and diminishes permeability and fluid flow.

The well known deficit in measured conductive heat flow relative to theoretical plate cooling models, requires that a significant fraction of available heat must be advected from the crust by fluid circulation for at least ~65 Ma. As with all other laterally variable parameters, our ability to assess the time-integrated effects of hydrothermal circulation on the shallow crust is hampered by a paucity of drill holes.

Basement boreholes as a function of crustal age

Only two holes penetrate completely through the lavas and into sheeted dikes (Holes 504B and 1256D), but both of these are in relatively young crust, 6.9 Ma and 15 Ma respectively. Although we have a number of moderate depth holes in Mesozoic crust (e.g., Hole 801B, 135 Ma, 317 m) we have no significant penetrations of crust in the age range 15 – 110 Ma despite the average age of ocean crust being ~65 Ma and the average age of crust being subducted ~77 Ma. The intensity of alteration in holes drilled into Mesozoic crust is difficult to interpret because it is not known whether this represents the cumulative impact of enduring hydrothermal alteration or alteration under different environmental conditions and by ancient seawater of different composition.



Left: Depth of penetration of holes (deeper than 50 meters below seafloor) into basaltic basement, as a function of crustal age. The boundaries between erupted lavas, the dike–lava transition zone, and the sheeted dike complex are placed at arbitrary depths based on Hole 504B stratigraphy. Black = DSDP holes, blue = ODP holes, red = IODP holes. Modified from IODP Expeditions 309 and 312 scientists (2006).

In particular, the absence of holes of intermediate age limits our ability to determine rates of hydrothermal alteration over periods of tens of millions of years. The depth of fluid penetration and of convective cooling remains unknown.

An ideal experiment to understand the evolution of fast-spread crust would be an age transect of sites spaced at 20-30 million year intervals along a crustal flow line, that includes one or more potential deep drill sites. Some holes should be deep enough (>3000 m) to investigate the extent of hydrothermal cooling of plutonic rocks, and these deep holes should be accompanied by shallow holes to establish local crustal variability.

Such a strategy would require many expeditions, several to each site. An initial strategy would be to drill a single deep hole, a significant distance into gabbro, in “hydrothermally mature” crust. Ideally, this site would be the back-up site identified earlier.

Other Science Questions

There was support for a number of other important science questions such as the volcanic and hydrological variability of young ocean crust, drilling overlapping spreading centers preserved off axis, other tectonic windows, and hydrothermal upflow zones and mineralization targets. Due to the personnel present there was little discussion in this group of observatories, and microbiological or active hydrologic experiments. Some of these science initiatives can be accommodated within the lithospheric priorities listed above, but others may have to be pursued outside a mission that targets drilling to the Moho. Drilling on axis in very young ocean crust without sediment cover remains extremely challenging as does drilling very hot rocks that host vigorous hydrothermal circulation. The fast spreading group encourages IODP to take seriously the technical development required to allow drilling to be an important tool in the understanding and instrumentation of active mid-ocean ridges at all spreading rates.

Lithosphere accreted at slow and ultra-slow spreading ridges

Co-chairs: Benoît Ildefonse & Jeff Karson

Since the early 70's when the "Penrose" layered model for the ocean crust (Penrose Conference Participants, 1972) was widely accepted, investigations of the oceanic crust by scientific ocean drilling, marine geological and geophysical techniques, complemented by ophiolite studies, have expanded our understanding of the architecture of the ocean crust in general, and of the high degree of spatial and temporal variability of slow-spread ocean crust in particular. In contrast to the apparently layered and spatially homogeneous oceanic crust created at fast spreading centers, crust created at slow and ultra-slow spreading centers is heterogeneous, both along- and across-isochrons, on a variety of scales, ranging upward from a few tens of meters. For example, the mid-sections of spreading segments along the northern Mid-Atlantic ridge are magmatically robust and supposed to be fundamentally similar to the majority of fast spreading ridges. This similarity is, however, very limited in space; close to segment ends, magma supply is diminished, crustal structure is heterogeneous and typically discontinuous, and a mixture of gabbroic intrusions and tectonically emplaced serpentinized peridotite, locally capped by lavas and/or sheeted dikes may be exposed on the rift valley walls or revealed by drilling in the ridge flanks (e.g., Cannat, 1993).

The group supported the consensus top priority of drilling a deep, full crustal penetration hole in fast-spreading crust. A majority also agreed that the nature of the Moho and the architecture of the ocean crust cannot be fully understood without a complementary and comprehensive investigation of slow-spread ocean lithosphere, with a long term goal of least one deep hole through non-layered, slow-spread crust. No attempt was made to reach consensus on the location of such a hole, or on priorities for complementary and/or preparatory drilling in slow-spread crust. A more focused activity, with access to data and significantly more discussion time will be required to resolve this complex issue.

Overarching themes

One fundamental goal of deep scientific drilling in the ocean crust is to characterize the variability of crustal architecture and to constrain the key forcing functions that control this variability. To achieve this goal implies, in addition to the objectives listed above for fast-spread crust, to assess the vertical and lateral variability of slow-spread crust on a variety of scales.

Although the identification and prioritization of drilling targets in heterogeneous slow-spread crust is difficult, the fundamental scientific objectives for deep crustal drilling are generally agreed upon. Some of these are relevant to both fast and slow spreading environments; some are beyond the scope of a functional Mission Moho.

To investigate the nature of the Moho in non-layered, slow-spread crust

Serpentinized mantle rocks are commonly incorporated into the crust (as defined seismically) at slow-spreading ridges. Drilling in this type of crust, down to fresh peridotites, would test various hypotheses regarding the nature of the Moho: 1) the boundary between the residual upper mantle and the igneous crust, 2) a broader zone of layered ultramafic and mafic rocks, 3) a serpentinization front, or any combination of these three. Particularly important is the objective of assessing the role of serpentinization in modifying the seismic signature of the crust and the transition to typical mantle velocities. This can only be investigated by drilling deep through a complete section of non-layered, slow-spread crust.

To compare slow-spread crust formed along magmatically robust segment mid-sections with fast-spread crust and determine the nature of layer 2/layer 3 transition

The hypothesis that magma-rich parts of slow-spreading segments are built through the same processes as fast-spread crust, and therefore have a similar, layered architecture, has never been adequately tested, with no deep hole drilled in such type of crust. The magma robust segment center in the northern Atlantic, south of the Azores Plateau (e.g. Lucky Strike Segment, DSDP site 332 at ~37°N) are possible locations for attempting deep drilling through the basalt and sheeted dikes, down through the gabbroic section to the Moho.

To sample an in situ *serpentinization front and fresh* in situ *peridotite*

Obtaining fresh residual peridotites is essential to fully characterize the composition and deformation of the oceanic lithosphere, and could be achieved by drilling through serpentinization fronts in outcropping peridotites. This was one of the objectives of IODP expeditions 304-305 at the Atlantis Massif, a oceanic core complex from the Mid-Atlantic Ridge (30°N), where a dominantly gabbroic section was eventually recovered, pointing to 1) the misinterpretation of geophysical data at the scale of the massif (10-20 km), and 2) oceanic core complexes (see below) not being the geodynamical expression of a magma-starved spreading (Karson, 1999; Ildefonse et al., 2006). The magma-poor end-member of spreading ridges seems to be more commonly found at ultra-slow spreading ridges (e.g. Gakkel Ridge, Southwest Indian Ridge), where peridotites are preferentially dredged in “smooth” seafloor areas (Cannat et al., 2006).

To understand how magnetic polarity transitions are recorded in heterogeneous ocean crust

In slow-spread, non-layered crust, all lithologies (serpentinized, magnetite-rich peridotites, mafic igneous rocks) can contribute to the bulk crustal magnetic pattern. Gabbros in particular appear to be a significant carrier of paleomagnetic record (Kikawa and Ozawa, 1992; Pariso and Johnson, 1993). Hence, the magnetic polarity transition should, in such type of heterogeneous crust, be controlled by processes of gabbro emplacement at depth, and by possible subsequent local tectonic rotations (Allerton and Tivey, 2001). This can be further tested by drilling through the expected dipping reversal boundary in the Atlantis Bank (Southwest Indian ridge).

To investigate the geochemistry and microbiology of in situ *hydrothermal systems*

Hydrothermal systems are fundamental scientific targets as they host microbial communities that we still know very little about. These communities are known to be significantly different from those supported by the now well-known black-smoker type systems (e.g., Kelley et al., 2001, 2005). Serpentinite hosted sites in particular, such as Lost City or Rainbow in the northern Atlantic, have never been sampled by drilling. Drilling through mineral deposits in basalt-hosted active hydrothermal systems has proved so far to be technically challenging, and coring is hampered by poor recovery. In order to assess the depth of seawater penetration in these systems, and to investigate related metamorphic and biological processes, drilling should be conducted in extinct sites (in locations such as TAG) where the relic reaction zone can be reached.

To investigate the interplay of magmatism and tectonic processes in construction of heterogeneous ocean lithosphere

A natural consequence of the reduced magma supply at slow-spreading ridges is the active role played by tectonics in crustal accretion (e.g., Lagabrielle et al., 1998), the most spectacular manifestation of which being the oceanic core complexes, that result from a complex interplay between detachment faulting and magmatic intrusion (e.g., Buck et al., 2005). Several oceanic core complexes have already been drilled, 2 of which host 2 of the 4 deepest drill holes in oceanic crust to date (Hole 735B, Atlantis Bank, Southwest Indian Ridge; Hole U1309D, Atlantis Massif, MAR). There is still a need, though, for a combination of both shallow (through the detachment fault) and deep drilling to fully describe their lithological and structural variety, and test current models for their development. Shallow drilling through the detachment fault might be best achieved using portable, seabed drilling tools, rather than "conventional" RCB coring. Oceanic core complexes are commonly, though not systematically encountered at ridge-transform inside corners. Whenever available, the combination of seismic and gravimetric data (e.g., Blackman et al., 2002; Canales et al., 2000) suggests that the crust is significantly thinner in these areas. A deep drill hole through the core of an oceanic core complex, down to mantle peridotites would inform not only the nature of the Moho in this particular context but also characterize accretion processes at depth (e.g., is the lower crust made of layered, primitive gabbros, or of serpentinized peridotites, or a combination of both?), and the modes of interactions between deformation and magma emplacement at the base of the lithosphere.

Some Possible Drill Sites In Slow-Spread Crust

Although the identification and prioritization of specific sites was beyond the scope of this workshop, the group identified a number of sites that offer potential for progress towards the objectives above. Some of the sites listed have already been drilled, others have seen so far little or no site survey activity. The list is intended to offer examples and is not necessarily complete:

Sites in Magma-rich Portions of Slow-Spread Crust

1. DSDP site 332 (MAR, 37°N 34°W)
2. Lucky Strike segment (MAR, 37°20'N 32°-32°30'W)

Site 332, ~ 1800 meters below sea-level, was drilled during DSDP Leg 37 and penetrated 310 m into basement. Drilling conditions and water depth are suitable for relatively deep, non-riser drilling into the upper, basaltic part of the crust. The Lucky Strike segment to date has not been specifically surveyed for drilling but is already well known. This area is of interest because it is one of the main sites of the MoMAR initiative (www.momar.org), offering a potential opportunity to link a deep borehole with local seafloor observatories.

Sites in Oceanic Core Complexes

1. Atlantis Massif (MAR, 30°N 42°W)
2. Atlantis Bank (SWIR, 33°S 57°E)
3. Kane megamullion (MAR, 23°30'N 45°30'W)

4. Godzilla megamullion (Parece-vela Basin, 16°N 139°E)
5. Uraniwa-Hills (Southern Central Indian Ridge 25°S 70°E)

Oceanic core complexes are numerous and offer a variety of sites that could potentially address our scientific objectives, including the opportunity to penetrate tectonically uplifted Moho. Hole 735B (1508 m deep) in Atlantis Bank and Hole U1309D (1415 m deep) in Atlantis Massif are currently the two deepest holes in slow-spread crust and among the five deepest holes in the oceans. Hole U1309D is open and in good condition, offering the opportunity to drill deeper at any time. Its apparent seafloor age is young (~2 My), which may be too warm to allow drilling beyond 2-3 km. Nevertheless, continuing this hole as far as possible with current, non-riser technology will provide valuable operational experience, testing drilling feasibility in relatively crust, and providing a valuable additional scientific return. The resulting operational experience is independent of spreading rate and will be directly relevant to fast-spread crust.

All five listed sites have site survey data available, and sites 2 to 4 are subjects for existing IODP proposals. Water depth at the Godzilla site is 5 to 6 km, too deep for riser drilling in the foreseeable future.

Sites in Ultra-slow-spread Crust

1. Eastern Southwest Indian Ridge (26-31°S 61-66°E)
2. Gakkel Ridge (Arctic Ocean)

A site in ultra-slow-spread crust could address objectives related to spatial variability of the crust. The abundance of mantle peridotite exposed along ultra-slow spreading centers suggests that there is an opportunity to access fresh peridotite by relatively shallow drilling. In the Indian Ocean, “smooth” sea-floor areas, interpreted as being the expression of the lowest magmatic activity (Cannat et al., 2006), are generally less than 4000 m deep and therefore accessible to future riser drilling by Chikyu. Gakkel ridge offers similar settings but its extreme northern latitude would require special (MSP) drilling arrangements.

Hydrothermal Sites

1. Rainbow (36°14’N 33°54’W)
2. TAG (26°10’N 44°50W)
3. Southern Knipovitch Ridge (74°N 7°E°N)

Rainbow and TAG are both sites of existing IODP proposals. The Rainbow site is located on a serpentinite-hosted hydrothermal system. The TAG site has been drilled previously. It is located on a basalt hosted hydrothermal sites (TAG) with associated massive sulfide mineralization. The rainbow proposal also address questions related to the possible role of hydrothermal systems in the origin of life on earth. The Knipovitch Ridge site has similar objectives related to sub-surface and seafloor biosphere. Effective spreading rate in the region is ~6-7 mm/y. The ridge is sedimented, and can be considered as an ultraslow equivalent to the Juan de Fuca ridge. Thick sediment covers the rift valley and rotated fault blocks. In spite of the high latitude and likely reduced appropriate weather window, the region is suitable for zero age drilling, and offset drilling of large low angle faults and detachment faults that likely expose lower crust and mantle.

Convergent Margin Sites

1. Izu-Bonin-Mariana forearc

A recent JAMSTEC seismic survey of the Izu-Bonin-Mariana forearc basin imaged a shallow Moho at approx. 5 km depth. This site has previously been drilled to 666 mbsf during leg 125 (ODP Hole 786B); it would be a good location for deep crustal penetration in a supra-subduction zone setting.

Evolution of the ocean crust

Chairpersons: Natsue Abe & Rob Zierenberg

The goal for crustal evolution studies is to understand how the lithosphere ages; in particular, how physical properties, chemical composition, structure, and microbial communities change with time.

As an oceanic plate moves away from the spreading center at which it was created, an evolving suite of water-rock reactions creates secondary mineral assemblages that fill pore space, replace pre-existing materials and fundamentally change the physical properties of the crust. This alteration is spatially heterogeneous, and variable in time, ranging from sub-millimeter scales to hundreds of kilometers.

In the context of a Mission Moho, the ideal approach to understanding crustal aging would be to drill a multi-hole transect along a seafloor spreading flow line, through a potential deep penetration site. Such an approach would place the deep penetration site in the context of the time-integrated physical and chemical changes that have modified the crust since its creation. Crustal drilling to date has been concentrated relatively close to mid-ocean spreading axes or close to subduction zones; very few holes have been drilled in crust of moderate age, ~20-80 Ma old. Although heat flow studies suggest that the crust becomes sealed, and the heat flux from the mantle becomes solely conductive, at ~60-65 Ma, there are no drill sites on crust of this age. In addition, an important aspect of alteration is its lateral heterogeneity and variability. In addition to cross-plate transect(s), clusters of holes at a few individual sites would contribute an understanding of the length scales of variability, local porosity, and geological structure through cross-hole experiments, logging and other local-scale studies.

The extent to which seawater circulation reaches the deep crust, and even the mantle remains a subject for debate. It is known, however, that serpentinite bodies of unknown size and shape are and important component of oceanic crust, particularly in slow- and ultra-slow-spreading regions. Whether serpentinite forms through reaction with seawater at depth, or through reaction with late-stage magmatic fluids, or both will require drilling into crust where serpentinization fronts may be present, and/or where a shallow, or tectonically uplifted Moho has been imaged, such as oceanic core complexes and slow-spreading segment ends.

The vitally important role of sub-seafloor micro-organisms in the chemical evolution of oceanic crust was not extensively discussed at this workshop (due to lack of expertise – IODP's Sub-Seafloor Life workshop was scheduled only two weeks later). The depth distribution of microbes in the crust is unknown but is likely influenced by host rock composition, temperature and permeability. Hence, determining the distribution of rock type, temperature and permeability as a function of depth and age of basement, and understanding how these distributions enhance or limit the distribution of microbial activity, are essential to understanding geochemical alteration. However, there is a very strong distinction in the techniques and approaches required to get rock and biology samples. Extraction and culturing of microbes is difficult because of potential contamination problems, and the veins and permeable altered zones that seem most likely to host microbial activity are often not recovered. Despite these difficulties, information about microbial-rock interactions can be gained from microbeam studies, even when microbes cannot be cultured. In the context of a Mission Moho, and given the current limited knowledge about the deep biosphere, biological considerations will not be a major factor in site selection. It is, however, especially important that operational strategies for deep crustal drilling be carefully designed to minimize contamination, and maximize opportunities for microbiological sampling.

Overarching Objectives

In order to maximize our understanding of the evolution of physical properties, chemical composition, geological structure, and microbial community structures as crustal aging proceeds, three primary objectives should be pursued:

Objective 1

To examine the interplay between magmatic, tectonic, hydrothermal and microbiological processes in determining the architecture of the oceanic crust, its mineralogical and chemical evolution, and changes in physical properties, in order to understand global geochemical cycling and the effects on the evolution of Earth.

Strategy

Addressing this objective will require 3-4 sites along a flow line to constrain the time-integrated effects of alteration. Each site would include one deep hole (~2 km) + 1-2 shallow (~500 m) holes to investigate length scales and variability of alteration. Having these sites along the same flow line as the proposed deep hole into mantle would be the optimum configuration. It would be particularly valuable if these sites extended from a US Ridge 2000 Integrated Study Site (ISS). The intense, detailed studies at the ISS would provide a wealth of additional information on zero-age crustal processes. There is an ISS at 9°N on the East Pacific Rise that would be the best candidate, and consideration should be given to this when determining where to site the deep drill site.

Objective 2

To quantify the depth of penetration of seawater into the oceanic crust and determine the controls on fluid circulation.

Strategy:

The proposed deep hole in Eastern Pacific crust as well as those proposed above along the flow line would provide some data points on the depth of fluid circulation, as will drilling at any crustal site. However, since seawater penetration depends on permeability, which varies by many orders of magnitude, the depth of fluid circulation is likely to be highly variable spatially.

A more direct approach would be to drill into either (i) an active, axial hydrothermal reaction zone, or (ii) a large, off-axis fossil reaction zone. The former is probably not feasible due to high temperatures, but the latter is feasible. Since the nature and geometry of the reaction zone are not known, the most likely candidates for such drilling would be large, but highly localized, relict sulfide deposits with a magnetic signature indicative of an upflow zone. A well known example is the relict mounds at the TAG hydrothermal site (Mid-Atlantic Ridge). A key element of this strategy is a second hole in a nearby unaltered area that could provide baseline chemical and physical properties.

Objective 3

To understand the role of *in situ* serpentinization in the evolution of the seismic Moho reflector, the crust-mantle boundary, the mantle-crust volatile flux, and the generation of reduced fluids that may sustain microbial metabolism.

Strategy:

A deep-penetration hole in East Pacific fast-spread crust will provide the first information on the crust-mantle boundary, and the possible role of serpentinization in its formation and evolution. Given that ultramafics are considerably more important in crustal formation and structure in slow-spread crust, it is important to investigate serpentinization in both environments. In this case, drilling two holes, one in crust formed near a segment end, and one at mid-segment, would constrain variations in crustal formation and structure, and in the style and role of serpentinization.

Technological Challenges

Improved core recovery in soft fault zone material and in hydrothermally altered rock is essential for hydrothermal and microbiological objectives. In particular, it is important to have better recovery of softer vein material, which is often lost during drilling. While the retrieval of cuttings on the riser ship may be helpful in this regard, sidewall coring, together with logging and imaging, might provide better recovery of the secondary alteration minerals, even though there will be fewer samples at discrete intervals. Oriented cores have long been desired and are necessary to investigate changes in magnetics during crustal evolution. Another requirement for investigating alteration in active systems is the ability to conduct logging at high temperature.

A Possible Timeline

Within 5 Years:

- Deepen Holes 1256D (super-fast spreading crust, Eastern Pacific) and 1309D (Atlantis Massif gabbros).
- Initiate drilling along the proposed flow line at least one site.
- Drill two holes in a slow spreading (MAR) segment to investigate the role of serpentinization in crustal formation and structure.

Within 10 Years:

- Complete the proposed age transect by drilling 2-3 sites.

Within 15 Years:

- Drill at least one complete section through the oceanic crust (most likely in the Eastern Pacific).
- Drill an active or fossilized hydrothermal reaction zone (most likely on the MAR).

Technology developments

Chairpersons: Jay Miller & Axel Sperber

Attendees: K. Becker, D. Christie, C. Eberling, M. Gelfgat, K. Grigar, R. Grout, G. Itturino, T. Janecek, N. Kyo, G. Myers, M. Takemura, D. Teagle, A. Skinner, D. Wilson

Strategies for progress at Site 1256

The technology group was asked to begin its work with a review of a position paper prepared by IODP-USIO TAMU staff in response to a request from SPC on potential ways to continue operations at Site 1256. The position paper is appended at the end of this section.

Operational scenarios considered by the position paper and the panel were:

1. Return to site and resume RCB coring using large viscous mud sweeps to keep hole clean.
2. Open existing hole and extend casing string to greater depth.
3. Drill a new hole designed for deeper penetration.

Basic data for Hole 1256D

Average penetration rates:
Leg 206—1.6 m/hr
Expedition 309—1.2 m/hr
Expedition 312—0.8 m/hr

Total depth: 1507 mbsf (1257 m into basement)
Casing sizes available: 20”, 16”, 13-3/8” and 10-3/4”
Casing sizes used: 20" and 16”

Since no specific depth target was identified prior to initiation of the borehole, the underlying premise of borehole engineering was to use as many as four, nested casing strings to get as deep as possible within as short a time as possible, continuously coring each interval. In implementation, these competing objectives required using as few casing strings as possible. The first two casing strings were required to isolate the borehole into basement. The additional casing strings were available if hole stability problems were encountered within a short distance (~ 200 m) from the bottom of the casing string, but were not required and Hole 1256D has now been drilled to nearly 1200 m below the casing string.

Although the hole appeared clean at the end of Expedition 309, Expedition 312 required several days and multiple pipe trips to clean out downhole debris before drilling could resume. Current depth is 1257 m into basement. The lower 400-500 m is clean and in gauge, but the upper few hundred m of uncased hole is more rugose. In response to a request from the science advisory structure, the operations team at IODP-USIO TAMU prepared a position paper to consider options for moving forward with, and achieving the best scientific return from, operations at Hole 1256D (see “Position Paper -- Operational Requirements for Returning to Hole 1256D” section below). The primary question as understood by the team was "Should we case Hole 1256D? In summary, the team, in consultation and agreement with members of the drilling team, suggests that the most prudent operation is to deepen the hole as far as possible with frequent mud sweeps (the successful deepening strategy used on Expedition 312). No attempt should be made to extend the casing, or otherwise remediate the hole for substantially deeper penetration, without a thorough engineering feasibility study.

The technology breakout group consensus was to consider Hole 1256D as a pilot hole for future deep penetration, Based in part on lessons learned from on-land (KTB and Kola) deep drilling, the eventual deep penetration hole should be re-engineered from the seafloor. The technology breakout group also recommended that, in general, any re-entry hole in basement should require an engineering design assessment, and any casing operation at Site 1256, whether remediation of the existing hole or creation of a new one, be preceded by engineering task force evaluation of lessons from the pilot hole.

Question for technology panel from the science panels

The technology panel also met with one of the science breakout groups in order to understand technological limitations that are inhibiting the achievement of science objectives. From this meeting a set of questions emerged:

1. Can a 3 km hole be drilled with the riserless ship?

There is nothing that precludes us from drilling a 3 km hole other than we have not done it. We need the proper location and appropriate engineering.

To enable a satisfactory engineering study, three important questions must be answered:

- What is the target depth? This must be an actual target depth and not a generic target such as “the bottom of the reaction zone”.
- What do you want to acquire when you reach that target? What are the dimensions of an acceptable sample?

What is required along the way? Is continuous coring always required? Are there alternative coring strategies? Are there other data (logging) requirements that might be affected by engineering decisions such as hole diameter or casing depth?

2. What are the temperature limits of drilling tools?

The Iceland geothermal group is drilling in 300°C formations and will soon be drilling in 400°C rocks. Technologically it is feasible to drill and core at 300°C. Using a downhole motor driven system, a 2 km hole can be drilled in 45 days without coring. With diamond coring systems (deeper and hotter), the pump rates have to be increased to increase cooling. Hole cooling seems to be the biggest issue.

3. What are the temperature limits of logging tools?

Most current slimline tools have a practical temperature limit of 100-150°C. Some tools can go as high as 200°C. The cable head is rated to at least 250°C. In Icelandic geothermal wells, tools are commonly run to 250°C. 300°C wireline tools and 400°C memory tools will be tested within the next two years.

4. What can we do to improve recovery rates (particularly in faulted and hydrothermally altered rock)?

Improve diamond drilling and mud motor technology. There have been significant advances in diamond bit technology over the last few years that might have an impact.

Spring stabilizer or adjustable stabilizers on coring tools can prevent jamming and loss of core.

5. Is hard rock core orientation possible?

Components are designed but no efforts are scheduled for integration and testing. HRCO is in the IODP-USIO technology roadmap and in the IODP-MI Engineering Development Panel technology roadmap.

6. What is the status of sidewall sampling with logging and imaging to get better recovery of secondary minerals?

Both are existing technologies that require engineering development to fit IODP applications.

Technological limits

The final panel discussion was focused on technological limits

Riser technology

- IODP is developing a 2500 m steel riser (delivery before 2013)
- IODP is committed to 4000 m riser (after 2013)
- Soon available in industry will be 3000 m steel risers
- Industry currently operates 2500 m aluminum riser
- IODP riser engineering may be simplified if a complex blow-out preventer is not required.

Drill String

- Steel 5.5-in and 5.875-in have been used to drill 11,000 m plus wells
- Aluminum 5.875 plus steel 5.5 have been used to drill 12,262m well Kola super-deep with 220°C bottom hole temperature
- Aluminum 6.625 has been used in Krivoy ROG Super-deep hole to 5500 m along with complete coring system featured motor driven retrievable core barrels
- Aluminum and steel 6.625 was designed for Russian scientific vessel “Nauka” 12000 m length.

Borehole logging technology

- Limited availability of slimline tools
- Developments in high temperature logging should be tracked.

Alternate coring systems for potential evaluation

- Continuous coring system (CCS)—originated from the Russian deep ocean scientific drilling project; since 1993 used as commercial deep water drilling system, operated from geotechnical DP vessel at water depths to 2000 m; has been used onshore as well.
- Diamond coring technology developments should be monitored
- Applications of fast drilling technologies applied in industry should be investigated
- Motor driven, high temperature drilling systems should be evaluated, in particular as to whether they can be adapted to coring systems.

USIO Position Paper -- Operational Requirements for Returning to Hole 1256D

(Shortened and slightly modified from an original draft provided by IODP-USIO TAMU operations)

Hole 1256D penetrates 1257 m into fast-spread oceanic crust (1507 mbsf) at the “Superfast site” in the Guatemala Basin. Drilling began during ODP Leg 206 and continued through IODP expeditions 309 and 312. It achieved one of the major unfulfilled objectives of ocean drilling, the sampling of a complete section from seafloor lavas through the dikes and into gabbros. A reentry cone is supported by 20-inch and 16-inch casing that seals off the entire 250 m sediment section and is anchored 20 m into oceanic basement. The emplacement of the cone and casing was a major engineering achievement and a first in ocean drilling.

In anticipation of potential future hardware needs, the reentry cone was configured to accommodate four different casing sizes (20-inch, 16-inch, 13 3/8-inch, and 10 3/4-inch). To date, only the two largest casing sizes have been two deployed, and it is possible that one or two additional casing strings (13 3/8” and/or 10 ¾”) could be installed. The multiple casing string strategy was designed to deal with a potential hole failure in the basalt section, within a couple hundred meters of the current depth of the casing string.

Recent logging data large show that large portions of Hole 1256D are out of gauge because of previous drilling, hole maintenance activities, and the many bit trips made during the course of three expeditions. The technical and engineering panel was asked to consider alternative methods for preserving this hole and enhancing the chances for extending its depth into the upper mantle. In principle, isolating enlarged sections of the hole with casing should greatly improve drilling conditions and enhance the ability to flush cuttings from the hole. If such a program were successful, it could potentially allow the deepening of Hole 1256D significantly.

The first key issue is to stabilize the upper section of open hole using casing. Strategies for achieving upper hole stabilization include:

(1) Enlarging the existing hole and installing 13 3/8” casing in a portion of the open hole below the 16-inch casing shoe.

To isolate the entire out-of-gauge section of the hole in this manner, a substantial length (>800 m) of casing would have to emplaced. Before 13 3/8” casing could be deployed, the entire section of interest would have to be enlarged from the minimum 10-inch bore to at least 18 ½”. To open the hole below the 16-inch casing to a minimum 18 1/2 inches would require specially designed hardware, such as under-reamers, bi-centered bits, or as yet undefined alternatives. Such an ambitious undertaking is without precedent in ocean drilling and presents a formidable challenge to our current technology.

(2) Enlarging the existing hole and installing 10 3/4” casing below the 16-inch casing shoe.

The advantage of this approach is that it requires the hole to be enlarged to only 14 3/4-inch diameter. This could potentially be achieved using a series of hard-formation 14 3/4-inch hole openers equipped with a 9 7/8-inch tricone pilot bit or perhaps a succession of body-hardened 14 3/4-inch tricone drilling bits. The disadvantage of this approach is that it precludes deployment of any additional casing. A potential disadvantage of this approach arises because the open hole diameter is not uniform and, therefore the pilot bit on a hole opener or bi-centered bit would not be able to accurately track the borehole in the enlarged areas. The result of trying to open such a non-uniform diameter basement hole would most likely result in a bore that would take the appearance of a warren with many non-concentric ledges and a significant drift. Because of the non-linear profile of the opened hole, it would be impossible to run and successfully land a significant length of 10 3/4-inch casing.

(3) A variant to the preceding two strategies would be to employ less ambitious lengths of both casing sizes, resulting in a shorter cased section.

A casing program of this magnitude has never been attempted. Regardless of the strategy proposed, to open and case any portion of Hole 1256D will require significant hardware and numerous pipe trips, as well as very slow penetration rates during reaming (<<1 m/hr). Operations would very likely extend beyond a single expedition, and involve substantial risk inherent in the use of untested technology. A thorough engineering feasibility study and risk assessment should be undertaken before any attempt to case any section of Hole 1256D.

More generally, the development and testing of the appropriate hardware to open and install extensive casing strings to enable deep drilling operations in ocean crust requires a concerted and focused effort. The panel recommends that a task force, consisting of senior ODL drilling and IODP operations personnel, in addition to appropriate scientific personnel be asked to formulate a realistic and achievable stabilization program for deep penetration holes. This task force should be empowered to bring in industry experts to review existing technology and enhanced hole cleaning techniques. The engineering design should be directed by the target depth and the scientific objectives to be met during and upon completion of drilling. It would be desirable to test various techniques on future IODP expeditions before they are applied in any deep penetration attempt.

Given the risks involved, and the need for appropriate development and testing, the panel recommends that deployment of casing in Hole 1256D is not an appropriate short-term option with the aim of deepening the hole as far as possible, or until time expires. The strategy would be to resume RCB coring using large volume (100-150 bbl), high viscous mud sweeps combined with frequent bit trips. A similar strategy was effective at clearing cutting debris from the hole during Expedition 312. Unfortunately, the large mud volume required depleted the onboard mud supply and the volume of the sweeps had to be reduced during the expedition. With appropriate planning, the vessel is equipped to maintain such an aggressive mud program. A conservative estimate is that 80 short tons of attapulgite equivalent would be needed to support the bulk requirements. However, it would be prudent to arrive on site with the bulk tanks topped off so that the ship is well equipped to handle any contingency. Assuming reasonable hole conditions and a average rate of penetration comparable to previous coring in this hole, it should be possible to deepen the hole by 500 meters in a 57-day expedition. This option has relatively low risk and could be carried out at short notice.

SUMMARY STATEMENT

Mission Moho statement

The dominant geologic process on planet Earth is creation of new oceanic crust, which hosts life and holds the history of Earth origin and evolution. The Moho is a seismic boundary assumed to represent the frontier between the crust and the mantle. We have not yet crossed this frontier, and the mission is primarily to determine the nature of the Moho. To drill and sample through crust into the mantle, is to understand the process of planetary renewal and how the surface of Earth is paved. The journey across this frontier and beyond into the Earth's mantle, the driver of plate tectonics, will take us through the primal architecture of this planet.

This mission will build upon and utilize new technologies to achieve the long-term (40 yr) goal of drilling to the mantle, which was the inspiration for scientific ocean drilling. The ability to conduct this mission through the IODP international partnership will create a legacy for generations to come.

This statement consolidates contributions from four working groups that were asked, on the final morning of the workshop, to draft a concise, easily understandable statement summarizing Mission Moho.

Consensus and debate on mission goals and strategy

The highest priority for Mission Moho is for projects that work towards the goal of a complete Mohole. This requires drilling through a complete ocean crust section, through the Moho, and into the uppermost mantle. The fundamental scientific objectives are to determine the architecture and composition of the ocean crust and the geologic origin of the seismic reflector that defines the oceanic Moho. Site evaluation for the ultimate Mohole should be focused on oceanic crust produced at a fast spreading (high magma flux) mid-ocean spreading center. This type of crust is predicted to be relatively thin and to have a simple layered architecture.

Full crustal penetration will require riser drilling technology to surpass the depth limit for riserless drilling, which is in large part determined by the ability to remove cuttings from the hole without controlled mud circulation. This limit appears to be no more than ~3 km below seafloor. IODP's riser vessel, R/V Chikyu is currently configured for a 2500 meter riser. Planning is under way to develop a ~4000 meter riser, ideally within a decade. This riser length effectively limits potential deep crustal drilling sites to water depths less than 4 kilometers. A 4500 meter riser would considerably increase the availability of potential deep crustal sites. Other highly desirable characteristics for deep crustal drill sites include:

- Seafloor age of at least 15 million years – required to allow for sufficient crustal cooling
- Formation at (super-)fast spreading rate – implies lower crustal thickness and that the hole will be more representative due to simpler, layered structure
- Relatively simple tectonic setting

- Subdued abyssal hill topography – implying limited crustal deformation
- Favorable location for logistics and weather conditions
- Latitude greater than 15 degrees – to ensure a significant magnetic inclination

In fact, there appears to be no suitable site that fulfils all these criteria. At present, Site 1256 in the Eastern Equatorial Pacific (Which fulfils all criteria except for latitude) appears to be at or close to the best location for a deep penetration crustal hole. The site was originally selected for its super-fast spreading rate, based on a prediction that this type of crust should be thin and simply layered. ODP/IODP Hole 1256D, after three expeditions, has reached a subseafloor depth of ~1400 meters, passing through pillow lava and sheeted dike layers into a gabbroic complex, believed to be the transition between crustal Layer 2 and layer 3. As part of Mission Moho, this hole should be deepened as far as possible into the lower crust using riserless technology. If the gabbroic complex proves to be the top of Layer 3, the prediction of thin crust will be validated.

Drill holes are spatially limited – essentially one-dimensional for many variables. For the scientific goals of deep drilling to be realized, every hole must be understood in its broader context. Before a final site is selected for a deep penetration hole, one or more candidate sites must be well characterized in terms of its geophysical parameters and geological setting, including both magmatic and hydrologic characteristics. Spatial context for "crustal" drill holes is ideally provided by site surveys that include geophysical (seismic, electro-magnetic) and geological (seafloor mapping and observation). These survey data can be complemented by, and understood in terms of, appropriate field studies in ophiolites. As we progress to deeper and deeper holes, site surveys will expand to include one or more shallower "pilot" holes.

Although Site 1256 is currently the best known site for full penetration of the crust, the search for, and evaluation of, potential alternative sites should continue in case Site 1256 proves to be less than optimal for deeper penetration using riser technology. Once the optimum site for a full penetration hole is identified (Site 1256 or elsewhere), a hole should be drilled and cased at this site in preparation for riser drilling through the remainder of the crust and Moho when riser technology is available for these water depths.

Drilling sections of crust and upper mantle produced at low spreading rates, and potentially with very different crustal architectures, is also an important goal of Mission Moho. Due, however, to the complexity of this problem, a consensus regarding either the priorities or the scope of drilling in slow spread crust was not achievable within the scope of this workshop. Some possible types of site include: a full crustal penetration site in a magmatically robust segment center; sites in tectonically exposed lower crustal and/or upper mantle sections; and sites in magma starved segments or near the lava-poor ends of more robust segments. As ongoing and future studies lead to a better understanding of the low magma flux crust, a consensus Mission Moho drilling strategy for the slow spread crust may yet emerge.

The evolution of the oceanic crust, i.e., understanding the alteration, thermal, and fluid-flow history in the crust is an important scientific goal, but not an essential element of Mission Moho.

Of potential interest to Mission Moho are possible interactions with other major programs. For example, the US Ridge 2000 program has targeted several "Integrated Studies Sites" – focus areas for multi-disciplinary projects that develop a whole-system “mantle-to-microbe” understanding of crustal accretion. Many of the key questions on evolution of oceanic lithosphere are being addressed at such sites. The better our knowledge of present day spreading processes, the better our experimental design and future understanding of ocean crust. Similar synergies can be found with the emerging ORION observatories, the European-led Mid-Atlantic Ridge (MoMAR) observatory site, and the Korean, Japanese and US program interests in the back-arc basins of the western Pacific.

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Mission Moho

Formation and Evolution of Oceanic Lithosphere

Sept 7-9, 2006, Portland, Oregon, USA

An international workshop sponsored by
IODP-MI/JOI/Ridge 2000/InterRidge

APPENDICES

Workshop Agenda

Thursday, September 7: Day 1

8:00 Introduction: Benoit Ildefonse and David Christie
8.05 IODP Mission Concept: Sue Humphris
8:15 History of "Mohole" planning: Jeff Fox
8:45 Report from Mohole Workshop in Japan - Toward a comprehensive understanding of the nature of Moho: Shoji Arai
9:15 Platform Capabilities. Current & vision for the future
  Chikyu: Kiyoshi Suyehiro
  US SODV: David Christie
9:45 Outcomes of the ODP “architecture of the Lithosphere” PPG: Mathilde Cannat

10:30 Architecture of ocean lithosphere, deep crustal penetration, and an update of the COMPLEX report hole concept: Jay Miller & Jim Natland
11:00 Age-depth and other site considerations for deep drilling: Doug Wilson
11:20 Opportunities using offset drilling / Tectonic windows: Benoit Ildefonse & Henry Dick
11:40 Evolution of ocean lithosphere: Andy Fisher & Damon Teagle
12:10 Ocean drilling and the deep subseafloor biosphere: Jim Cowen

13:30 Mission Moho, updating our vision for ocean lithosphere drilling: Peter Kelemen

14:00 Charge to breakout groups: David Christie & Benoit Ildefonse

14:10 Breakout groups :
  Formation and architecture of the ocean crust (chairpersons: Bob Detrick & Chris Macleod)
  Evolution of the ocean crust (chairpersons: Natsue Abe & Rob Zierenberg)
  Technology developments (chairpersons: Jay Miller & Axel Sperber)

16:30 Plenary session.
  Report from breakout groups and discussion

18:30 Poster session and cocktail reception

Friday, September 8: Day 2

8:30 Plenary session, Charge to breakout groups
8:45 Breakouts groups (continuing from day 1)

11:00 Plenary session. Report from breakout groups, discussion

13:30 Breakout groups
Lithosphere accreted at fast-spreading ridges (chairpersons : Damon Teagle and Rob Zierenberg)
Slow and ultra-slow spreading ridges (chairpersons : Benoit Ildefonse & Jeff Karson)

16:00 Plenary session. Report from breakout groups, discussion

18:00 Optional session
Information and advice on proposal writing

Saturday, September 8: Day 3

8:30 Plenary session, final discussion

10:30 Breakout groups
Discussion of Mission Moho statement
11:00 Plenary session, final discussion
12:30 End of Meeting

13:30 report drafting (Steering committee + Breakout session chairs)

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Historical Background

In April 1961, the first successful drilling and coring of oceanic basement was achieved offshore the Guadalupe Island. A few meters of basalts were recovered, below about 3800m of water. This remarkable breakthrough, beautifully reported by John Steinbeck in Life magazine, was aimed to be the first stage of project Mohole, a much more ambitious project to drill through the ocean crust to the Mohorovičić discontinuity. Over the last 45 years, this fundamental goal has been reiterated in the successive science plans of DSDP, ODP and IODP. The early days of ocean drilling in the ocean crust can be and were told in various ways (e.g., Bascom, 1961; Shor, 1985). What follows is a brief history of the quest for the Moho, and some of the lessons learned over the years, extracted from a presentation prepared for the workshop by P. Jeff Fox (TAMU). The second of section is a short summary of how the Moho is defined, provided by Manik Talwani (IODP-MI).

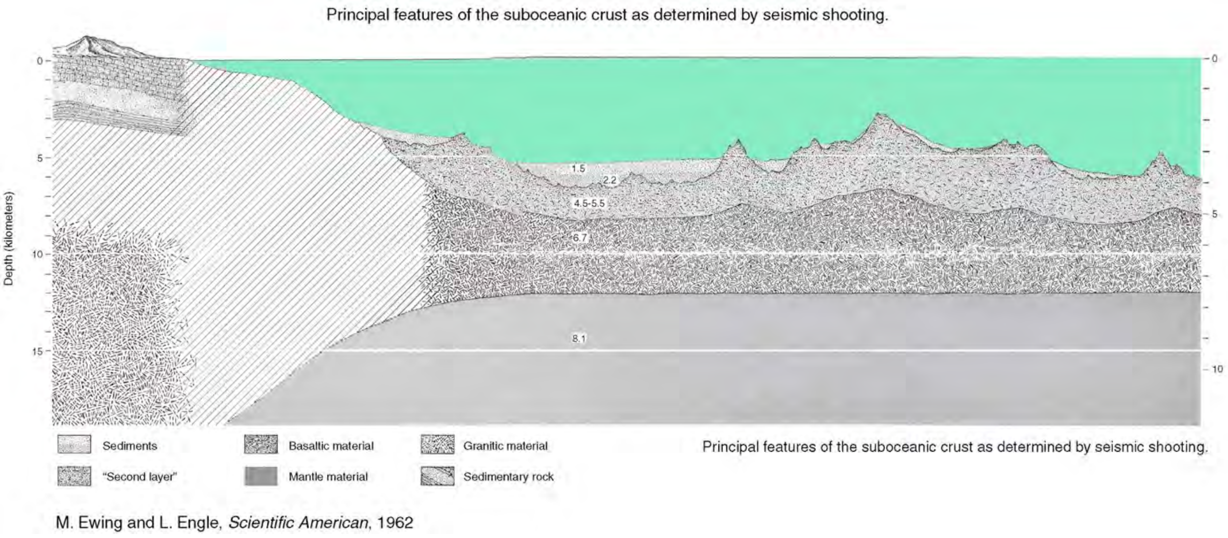
The quest for the Moho

P. Jeff Fox

Following the discovery of the seismic discontinuity between continental crust and mantle by the Croatian scientist Mohorovičić in 1910, there was great interest in the nature of this fundamental boundary and there were lively debates regarding its origin – whether it represented a phase change or a compositional change.

Shortly before World War II, Maurice Ewing and colleagues shot a land-sea refraction line across the coastal plain of the east coast, the shelf and slope of the eastern US, and into the deepest portions of N. Atlantic oceanic crust. This work documented that the depth to Moho went from as great as 30 km at the landward end (typical of continental crust) to just 10-12 km below the sea surface on the ocean end. Following World War II, the Office of Naval Research (ONR) funded an initiative to determine the acoustic characteristics of the ocean basins, resulting in Woods Hole Oceanographic Institution (WHOI), Lamont-Doherty Geological Observatory (now the Lamont-Doherty Earth Observatory (LDEO)) and Scripps Institution of Oceanography (SIO) carrying out pioneering refraction work in Atlantic and Pacific in late 1940s and 1950. Shot points were widely separated by km to > 10 km and a very averaged, but consistent, picture emerged suggesting a three-layered seismic structure, a well-defined Moho, and consistent layer thickness.

The Moho came to be recognized as a boundary of fundamental importance found throughout the global ocean. The apparent accessibility of the Moho in the oceans, and the apparent homogeneity of the overlying crustal material in terms of thickness and velocity structure led to the "Rosetta-Stone like" notion that a single hole through ocean crust to Moho would allow definition of the properties of 70% of the Earth's surface (Figure 1).


Principal features of the suboceanic crust as determined by seismic shooting.

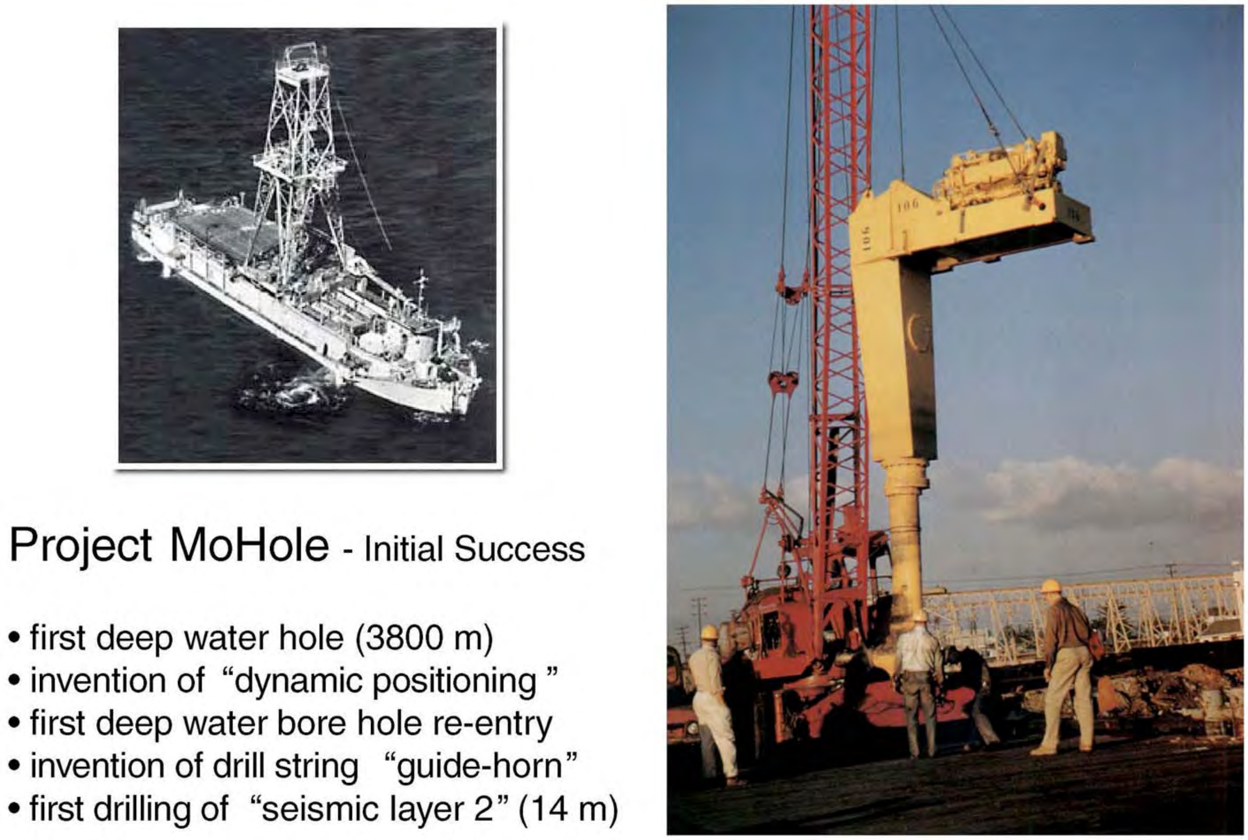
M. Ewing and L. Engle, *Scientific American*, 1962

Fig. 1 - A seismic refraction profile that illustrates the perspective that the oceanic crust (Layer 2 and basaltic material, later called Layer 3) was regionally homogenous.

Phase 1: Scientific Ocean Drilling – Project Mohole

As Art Maxwell recounts in an Oceanus article (An Abridged History of Deep Ocean Drilling, Oceanus, v. 36, no. 4, p. 8-12), in 1957, Walter Munk, a physical oceanographer at SIO, and Harry Hess, an igneous petrologist at Princeton, suggested a project to utilize the emerging offshore drilling technologies and capabilities to drill through the oceanic crust to Moho. By the end of that year, like-minded individuals refined the idea over breakfast in Munk's house, and took the idea to ONR. The idea was viewed favorably, and Gordon Lill of ONR chaired a committee that submitted a proposal to the National Science Foundation (NSF) for a feasibility study to determine whether offshore drilling technology was capable of achieving the science goals. Proponents of this project were members of a loose affiliation called the American Miscellaneous Society (AMSOC) – a group of earth scientists encouraged by ONR to think "out of the box". NSF turned the proposal down, not on its merits, but because there was no formal organizational structure to manage and take responsibility for such a project. The AMSOC group then went to the National Academy of Sciences/National Research Council, and a Project Moho Committee was formally constituted. A proposal was resubmitted to NSF with an ocean engineer on the National Academy staff, Willard Bascom, as project leader. This time they were successful.

In 1960, Willard Bascom hired the services of a floating drilling rig, CUSS 1 that was more barge than ship. CUSS I had been built by a consortium of four oil companies – Continental, Union, Shell and Superior Oil – but had recently been acquired by Global Marine Exploration (Figure 2). In 1961, off Guadalupe Island, Mexico, CUSS I drilled the first deep-sea hole in 3800 m of water. They penetrated 200 m of sediment, and sampled 25 Ma old sediment at the base of sedimentary section, and also recovered 14 m of basalt. These results established that at this location, seismic layer 2 was basalt and, most importantly, that drilling in the open ocean was feasible.



Project MoHole - Initial Success

- first deep water hole (3800 m)
- invention of "dynamic positioning "
- first deep water bore hole re-entry
- invention of drill string "guide-horn"
- first drilling of "seismic layer 2" (14 m)

Fig. 2 - A photograph of the drilling barge CUSS I (upper left) and one of the four propulsion systems that were positioned fore and aft to port and starboard providing dynamic positioning.

However, over the next few years, Project Mohole foundered on the rocks of mismanagement, politics gone bad, and escalating costs, coupled with deep divisions in the scientific community. A proposal was issued for a contract for a drilling ship that attracted many bidders – some of whom were more qualified than others, but all were interested in the money. Congressional delegations associated with the NSF appropriations committees got involved, and the contract went to a company not ranked highly in terms of technical capabilities. The company, Brown and Root, went out for shipyard bids and costs for the ship more than doubled to \$47 million, with a total program cost estimated to be >\$100 million.

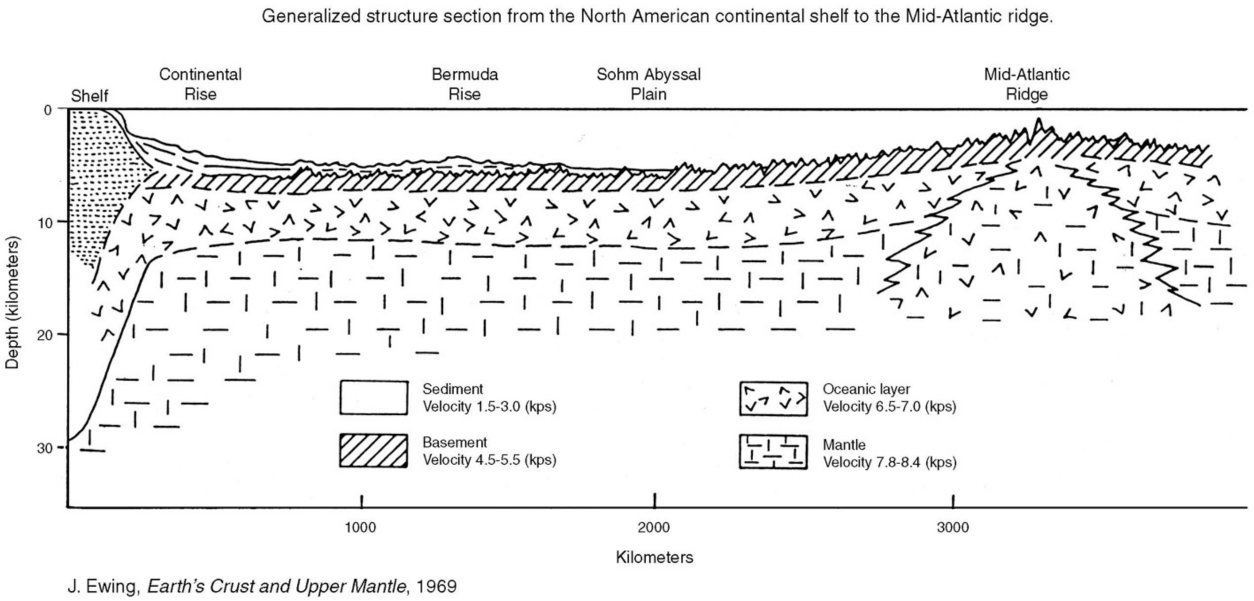
In parallel with the contractual/fiscal issues, the science community was split, with Harry Hess and colleagues arguing for a "Project Mohole" (drill directly for Moho) and Hollis Hedberg and colleagues arguing for a phased approach – drill and core the sedimentary section first before trying to drill through the crust to Moho. The additive effect of these two problems was that Congress passed language in the 1966 appropriations bill that forbade NSF from proceeding with the project. Project Mohole was dead.

Phase 2: Scientific Ocean Drilling – More Broadly Defined

In the early 1960s, the directors of four large oceanographic institutions – WHOI (Paul Fye), LDEO (Maurice Ewing), Miami Institute of Marine Sciences (Walton Smith), and SIO (Roger Revelle) felt that the oceanographic labs had to be better organized to lead scientific ocean drilling, so in 1964, they founded Joint Oceanographic Institutions Deep Earth Sampling (JOIDES). NSF was supportive of institutional harmony and provided JOIDES with funds to contract a small drilling barge, CALDRILL, to further test dynamic positioning in deep water. Drilling tests were conducted off the east coast of Florida in 1965, with LDEO managing the project. Based on the success of the CALDRILL project, NSF awarded SIO a 12.6 million contract to establish the Deep Sea Drilling Project (DSDP) in 1966.

In August 1968, the Glomar Challenger operated by Global Marine Exploration, began the first of DSDP pioneering legs. Over 15 years (1968-1983) DSDP sailed 600,000 nautical miles on 96 cruises, collected over 97 km of core, and established the first order geologic properties of the ocean basin.

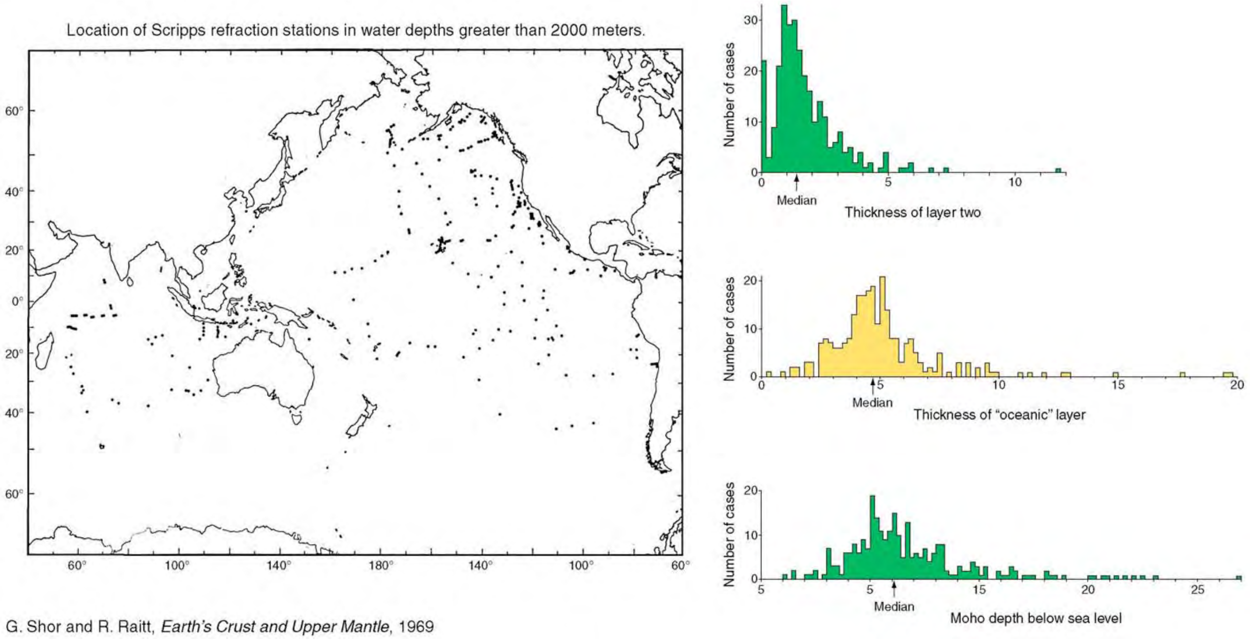
With the birth of DSDP, scientific ocean drilling was driven by a scientific mandate to investigate all aspects of the ocean floor: crustal architecture, plate boundary tectonics, convergent margin processes, spreading centers, sedimentary history/processes, and passive margins. As such, the singular focus to drill through the crust to the upper mantle was lost. Project Moho proponents were members of the crustal architectural group and had to share the available drilling time with other competing scientific constituencies. Moreover, the project was global in nature, and there were many competing scientific constituencies and many globally distributed problems. The pressures to address a diverse set of compelling scientific problems made it hard for the ship to sit still and drill in one location. In addition, plate tectonics made the ocean basins much more interesting: convergent margins, marginal basins, axes of plate accretion, hotspots/plume volcanism etc. Drilling to Moho had competition.



J. Ewing, *Earth's Crust and Upper Mantle*, 1969

Fig. 3 - An example of an interpretation of seismic refraction data suggesting that oceanic crust was isotropic at a basin-wide scale

At a fundamental scientific level, evidence for a spatially and vertically heterogeneous oceanic crust started to emerge. This revelation came from different scientific perspectives – higher resolution seismic refraction studies, and the recognition of the significance of ophiolites. Although the interpretation of some refraction studies promulgated the notion of crustal homogeneity at a basin wide scale (Figure 3), refined experiments and careful examination of a new generation of refraction data suggested that the crust was more seismically heterogeneous than originally thought (Figure 4). By the late 1960's, ophiolites were recognized as slices of oceanic crust and mantle, obducted and exposed on land. They confirmed the first order compositional and structural layering of oceanic crust, but also demonstrated that the thickness of igneous units is spatially variable, both within and between individual ophiolites, and that many ophiolites have undergone complex, water-rich metamorphic transformations that have modified the igneous crustal architecture.



G. Shor and R. Raitt, *Earth's Crust and Upper Mantle*, 1969

Fig. 4 - An example of an interpretation of seismic refraction data suggesting that the oceanic crustal components were more heterogeneous than originally thought

Phase 3: Scientific Ocean Drilling – A More Nuanced View of the Oceanic Crust

Throughout the 1970s, as the ability to access and characterize the oceanic crust and underlying upper mantle improved, and a more accurate picture of the oceanic crust emerged.

Carefully navigated dredges and submersible transects recovered the full suite of oceanic and upper mantle components – sometimes pristine, but often metamorphosed and deformed, attesting to a complex history. Moreover, DSDP crustal drill holes sited on "geophysically normal" ocean crust in the North Atlantic recovered gabbros and ultramafics at very shallow crustal levels. Geophysical investigations resolved the oceanic crust in greater detail demonstrating variations in crustal thickness and velocity structure at a range of scales, and differences between slow and fast accretion. Physical property studies of recovered rocks helped relate seismic data to the recovered suite of igneous, ultramafic, and metamorphic rocks, and it became recognized that velocity gradients and/or velocity boundaries could be igneous or metamorphic.

By the late 1970s and 1980s, there was an emerging consensus that there was crustal and upper mantle heterogeneity on all scales reflecting variations in a range of processes. Significant variations in magmatic budgets and tectonic processes associated with variations in spreading rate and proximity to tectonic boundaries (i.e., transform faults) were recognized as producing significant crustal complexities. The tectonic fracturing of the crust along the ridge axes was associated with hydrothermal circulation that could significantly alter the initial igneous layering and structure.

Although Project Mohole had died politically and as a funded project in 1966, it was through the late 1970's and early 1980's that the scientific rationale for Project Moho evolved in response to these new geophysical and geological data. Although it was still considered important to drill through the crust into the residual upper mantle, there was now the understanding no single hole would capture the igneous, structural and metamorphic characteristics that integrate spatially and temporally to create the oceanic crust and upper mantle.

Given these observations, drilling strategies were adjusted accordingly. A concerted effort has been made to utilize the exposures of plutonic and ultramafic rocks made accessible by tectonic processes. More recently, there has been a concerted effort to drill a deep hole into fast-spread crust, given that there is a sense that crust created in this environment is more spatially homogenous.

Lessons Learned

Given the documented complexity of the oceanic crust and upper mantle, it is clear that a Project Mohole for the 21st century must be much more than one deep hole – it needs to be an exploration at a global scale of the oceanic crust and underlying upper mantle. The community must create an integrated strategy that builds an investigative mosaic, rather than pitting one regionally bound constituency against another (e.g., the SW Indian Ridge against Pito Deep). Drilling proposals should integrate a mix of clever investigations, instrumented where appropriate – petrological, metamorphic /hydrogeologic, instrumented where appropriate, and microbiology. This approach will take advantage of a large and broad investigative constituency to address a family of fundamental questions.

Drilling in igneous/metamorphic rock is tough going so it will be important to utilize new drilling technologies and tools. Funds will need to be allocated to develop these tools and the program needs to set aside time to test them. Many different interest groups compete for limited resources and, therefore, it is essential that the oceanic lithosphere community put forward well-articulated proposals requiring advances in technology. Finally, given that the other constituencies competing for drilling time are well organized and are proposing well articulated and integrated experimental programs, it is important that the many voices that characterize the community of scientists studying the many aspects of oceanic lithosphere become a persuasive and harmonious chorus.

The Seismic Moho

Manik Talwani

Seismically, Moho has been delineated by three different methods: earthquake studies, seismic refraction and seismic reflection.

Earthquake Studies

The Mohorovičić discontinuity more colloquially known as Moho was first discovered through studies of P-wave arrivals from earthquakes by the Yugoslavian seismologist Andrija Mohorovičić in 1906. It should be noted that the sub-Moho velocity that Mohorovičić found was about 7.5 km/sec. Also while the presence of this interface was discovered, its detailed topography was not determined.

Seismic Refraction

It was not until several decades later that seismic refraction more definitively verified the presence of Moho under the continents at the depth, generally, of 30 to 40 km. Subsequently, in the 1950s and 1960s seismic refraction at sea verified the presence of Moho at the much shallower depth of about 10 km in oceanic areas. The sub-Moho velocity under both continents and oceans was found to be about 8.2 km/sec. This velocity began to be considered as the "normal" sub Moho velocity, although in many locations, for example, near ridge crests and continental margins, the velocity was in the range of about 7.5 to 7.8 km/sec. It is important to note that even for "reversed seismic experiments" the detailed structure of Moho is not revealed, offsets or gaps in Moho are not determined, and Moho is assumed to be a planar interface. Nor is any information gathered about the structure and/or layering within the overlying crustal layers.

Seismic Reflection

Seismic reflection carried out from the 1970s on revealed much more information about Moho, especially its structure, including the presence of offsets, or discontinuities. Seismic reflection also gives an indication of what might lie above and below the Moho. Layering or its absence, especially above Moho, and particular characteristics in the crust are often revealed by the seismic reflection image. Amplitude vs. offset studies carried out on seismic gathers can give an indication of the kinds of materials involved at each reflection interface. Most importantly, the nature of the reflectors in the crust, or their absence might provide correlations and inferences regarding the rocks that are present. For this reason, excellent seismic reflection studies should be extremely useful, not only in choosing drill sites, but also in evaluating their normalcy and possibilities of extrapolation from the drill sites.

The usefulness of seismic reflection does not suggest that sites being presently being considered be abandoned, but rather that even at these sites a detailed reflection study (supplemented by refraction for obtaining velocity information) should be considered very important.

Gravity

A word about gravity. The site chosen should be consistent with observed gravity values to avoid anomalous situations. For example, if in relatively shallow water Moho is found to be at a shallow depth and the gravity anomalies do not have large values, clearly the site is anomalous and possibly not suitable for drilling the single Mohole.

For the very expensive Mohole it should be quite obvious that all the various geoscience disciplines should be employed to select the most appropriate site.

Lessons Learned About How to Run a Mission Workshop

Rosalind Coggon, Emilie Hooft, and Stephanie Ingle

Here we discuss some ideas and suggestions on how to make a mission workshop most successful for achieving workshop goals, initiating a strong IODP mission proposal, and ensuring inclusion of all nations and generations of scientists in the process and outputs of the workshop. We focus on three elements: 1. Clearly identifying the purpose of the workshop; 2. Conducting the workshop; and 3. Post-workshop planning.

Clearly stating the purpose of the workshop

1. The purpose of the mission workshop should be clearly outlined at the beginning of the meeting.

- State the workshop objectives.

A clear statement of the meeting objectives will help avoid confusion about the goals of the workshop discussions. In particular, it is useful to clarify the balance between exploring areas of common interest as an international community and focusing on what is needed for a successful mission proposal.

- Announce required meeting outputs.

Knowledge of the required structure of the meeting outputs (e.g., reports/proposals) should also help structure and focus the discussion throughout the meeting. For example, the guidelines for writing a mission proposal would help in determining the level of detail necessary in scientific decisions made during the meeting, e.g. whether it is necessary to choose and rank specific drill sites. This should help ensure that consensus be reached on the most relevant issues.

2. The purpose of the mission should be outlined at the start of the meeting.

- Identify key scientific issues to be addressed by the mission project to develop a mission statement.

For a mission proposal to be successful it must have a clear and exciting focus. Coming to a consensus on the mission statement and discussing the relative importance of the various elements should guide later discussions.

- Define the scope of the mission.

The scope of a mission is not set in stone and discussing the spectrum of ideas possible, and their relative importance to the mission, will help to clarify this. Some scientific objectives are inherently very strong but may be of secondary importance in addressing the mission goals. In the case of Mission Moho, people had very different ideas, e.g. some thought the scope of Mission Moho was simply to drill a complete section of ocean crust, others thought it was to investigate thoroughly the nature of the Moho, the architecture of the crust, or the evolution of the crust, by drilling in several locations. These issues must be properly debated to result in a consensus on the scope of the planned mission.

3. The long-term mission vision should be discussed at the meeting.

- Short-term (~5 yr) tangibles toward mission objectives.
- Medium-term (~10 yr) goals that are attainable assuming technological capabilities arrive as anticipated.

- Long-term (~20 yr) vision and the new technological advancements required to achieve overarching scientific/mission themes in the next 20 years.

A mission is clearly a complex and long-running project; therefore, we must have plans on different time scales. Planning a mission requires balancing experience and technical know-how of the older scientists with the vision and excitement of the younger generation. The younger generation will carry this mission to fulfillment and can hope for new technological advances that will bring some of their vision to fruition. During the mission Moho workshop discussions there was an emphasis on short term plans. It is difficult to ‘plan’ what to do in 20 years because decisions are dependent on the results of as-yet unplanned site survey cruises, unavailable technology, and results of preliminary drilling. Nonetheless, it is crucial to excite the younger generation (and the tax payers) and adequate time should be spent on long-term planning and visions for the mission.

Conducting the meeting

1. Ensuring the objectives of the workshop are met:

- Breakaway discussion groups should be given clearly identified tasks, and if relevant, a list of decisions they should return, to help focus the discussion throughout the meeting and ensure the required consensus is reached. (Obviously, the planned discussions may evolve throughout the meeting depending on the decisions made). It might help if breakaway discussion sessions were shorter, to keep them focused.
- The discussion and the outcomes should be presented in the subsequent plenary session in such a way that they can be handed to those writing the workshop report.

2. Ensuring people are included:

Some groups (e.g. those who didn’t speak English as a first language, who hadn’t been in the field as long as others, or weren’t familiar with the DSDP/ODP Site numbers or IODP committee acronyms) find it harder to keep up with the discussions; there is also uneasiness amongst some participants about voicing opinions. Below are some ideas on how to make the process more inclusive and ‘user-friendly’ in order to: 1) maintain the international spirit of the IODP, 2) hear opinions, insights, and questions from a community-representative group, and, 3) recruit the next generation of scientists who will, in all likelihood, carry out the majority of the science resulting from individual expeditions and who will inherit the Mission’s scientific legacy.

- Acronyms, leg, expedition, and drill site numbers should either be well-defined up front or avoided entirely until all attendees are familiar with these. A suggestion is to provide attendees with a list of common acronyms and a brief description (location, science outcomes, etc.) of relevant legs, expeditions, and/or sites.
- Small group discussions, with participants seated facing each other, may better foster involvement of everyone. Each small group should have, or choose, a chairperson who ensures that certain people do not monopolize discussions, and that everyone is given a fair chance to speak.
- We suggest building consensus in small groups first, then trying to build consensus on these outcomes with the entire group; doing this early in the workshop process, after the introduction and background information is provided may forge consensus early rather than later.
- Frequent movement of individuals between small discussion groups is not helpful. They are likely to enter unaware of the progress made prior to their arrival and may only express their

ideas and then move on without listening to subsequent debate. This type of movement should be discouraged from the beginning, with movement between these short, coherent sessions, at mid-day, for example, encouraged to allow for a wider exchange of ideas and more comprehensive discussion.

- Hand raising as a means of voting is not common in all cultures in the IODP and those uneasy about speaking up are also hesitant to express their opinion publicly. This may be unavoidable for decisions necessarily made quickly, however for important decisions, another method should be chosen.

Post workshop planning

Transitioning from the workshop to the plenary mission proponent group requires some thought. Given the debates during the meeting, the dominance of some people, and the lack of consensus on some issues, it is important that the continuing planning of a mission proposal be transparent, both to the ocean lithosphere community and the wider science community. Some specific issues that should be addressed or identified before the meeting is concluded include:

- Main objectives and outputs expected from the meeting.
- The time frame or deadlines for the tangible outputs.
- A proposed (national – specialty – generational), general make-up of who will be involved and why.
- Identify how the process will be made transparent to both our IODP community and the scientific community at large.

In summary, the process of writing a mission proposal will be easier if consensus on the scientific objectives and scope of the mission, and a basic drilling strategy (not necessarily site specific) are reached during the workshop. This reduces the need for major decision-making by a sub-set of the community, and hence alleviates potential transparency issues. Furthermore, an inclusive workshop that does not alienate parts of the community encourages their involvement in the proposal writing process, and perhaps more importantly, in the long-term implementation of the mission strategy.

Links to Preexisting documents

- IODP Initial Science Plan :
http://www.iodp.org/isp/

- Interridge "The next decade" Science plan 2004-2013 :
http://134.245.210.163/public_html/ORGANIZATION/science_plans/IR_next_decade.html

Ridge 2000 Science Plan :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=786

Mission Specific Platform Science Plan :
http://www.bgr.de/ecord/index.html

"Road to the Moho" in the 2000 JOI/USSSP report "Opportunities in Geochemistry for Post-2003 Ocean Drilling" :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=784

ODP Architecture of the lithosphere PPG, summary report, 2003 :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=783

1996 Woods Hole workshop :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=785

COMPLEX, Multiple Platform Exploration Conference on of the Ocean, 1999 :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=808

Keynote Presentations

Chikyu Capabilities. Current and Vision for the Future

Kiyoshi Suyehiro, JAMSTEC

The technical ability to drill to the Moho will be provided by drilling vessel “CHIKYU”. Chikyu (meaning Earth in Japanese), the world’s only scientific riser drilling vessel, was delivered to JAMSTEC in July, 2005 (Figure 1). Since then, JAMSTEC has been conducting System Integration Tests, which will continue until its IODP expedition begins in September 2007. Following the completion of riser-drilling tests in late 2006, Chikyu will conduct more challenging riser drilling operations in potential hydrocarbon bearing environments in the Indian Ocean. These activities will bring Chikyu to full operational status.

In 1996, an international workshop on riser technology was held in Yokohama to discuss scientific objectives in terms of several model holes, including the Moho target. For eventual penetration of the oceanic crust, a phased approach, moving from the existing 2500 m riser, to a 4000 meter riser was recommended. This approach requires sound engineering development, based on the following anticipated conditions at the Moho: temperature about 200 °C; crustal age 20 Ma and thickness 6-7 km.

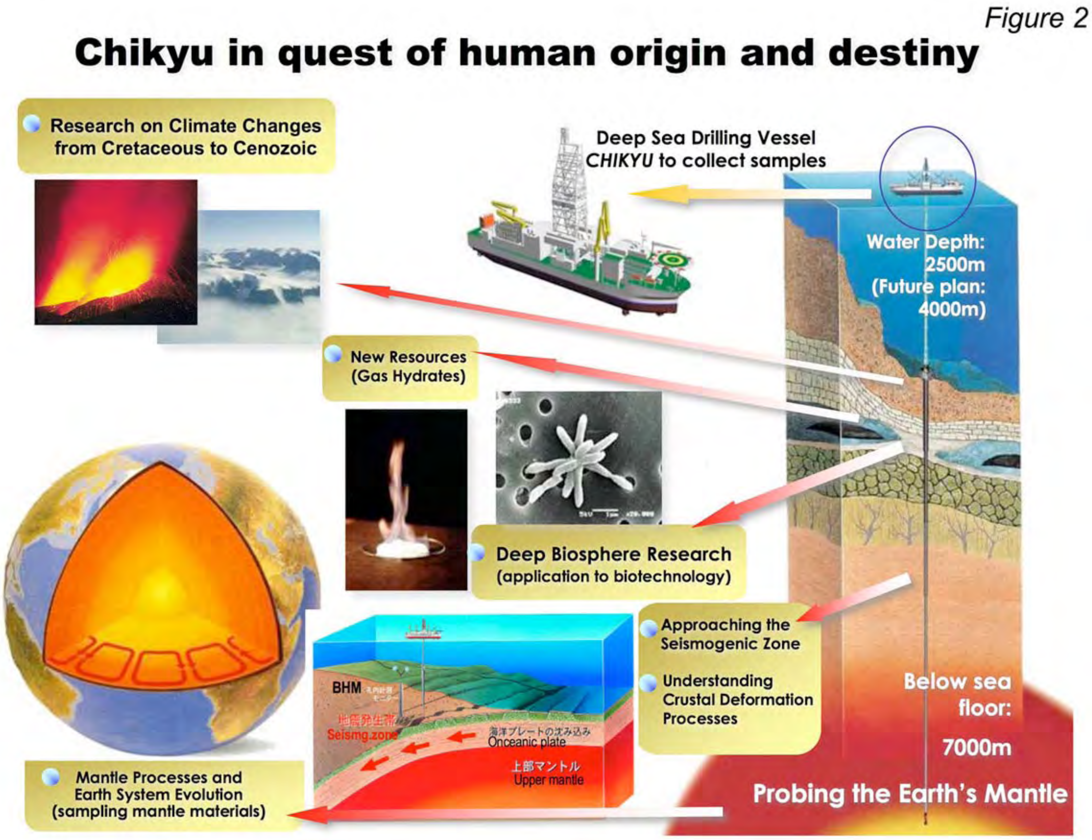


Figure 2

Chikyu in quest of human origin and destiny

Chikyu is expected to be the first drilling vessel to have a 4000 meter water depth riser capability. Figures 3 and 4 illustrate the unique Chikyu riser pipe handling and blow-out prevention device, which enables continuous mud circulation during drilling and coring operations. Mud circulation provides cooling, lubrication, cleaning, and pressure control of the hole for stable deep penetration to the full 10,000 m drill string length. The return of cuttings to the ship for physical and chemical analysis is an additional advantage.

The four-storey laboratory stack houses state-of-art equipment for physical, chemical, and biological analyses to meet the requirements of the wide spectrum of earth and life scientists (Figure 5). An identical equipment suite is operational at Kochi Core Center, jointly operated by Kochi University and JAMSTEC (Figure 6). In addition, Kochi Center provides core sample storage as well as high-end equipment, such as ICP mass spectrometers, for visiting scientists.

Chikyu brings riser capability to IODP science. To supplement its drilling and sample recovery capabilities, IODP demands sophisticated and integrated analyses of core samples, cuttings, logging data and site survey data. CDEX and Kochi Core Center are tasked to respond to such demands.

For the upgraded Chikyu to challenge the Moho and the mantle, the present Chikyu must first prove and show its capabilities and potential. As Figure 2 shows, we will have to recognize that we are not just targeting a hole to the mantle. The whole mantle processes and earth system evolution are in question. The 21st Century Mohole will be justified only when it is framed in such a context and at its focal point.

Figure 3

Riser rack

27 m long
1.2 m OD
0.5 m ID

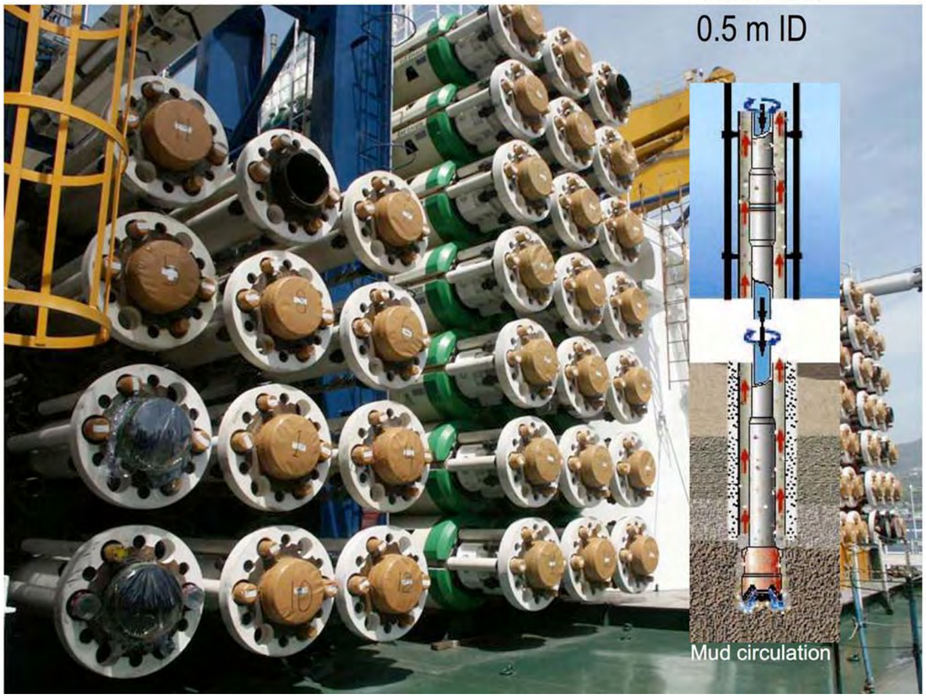
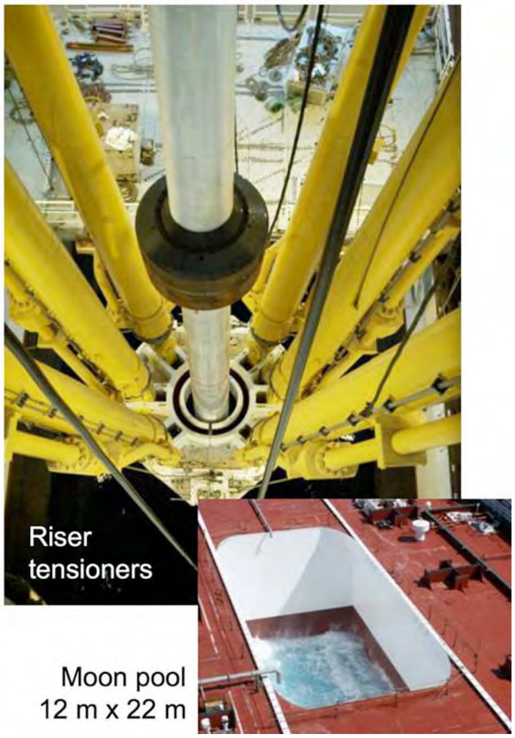


Figure 4

Subsea

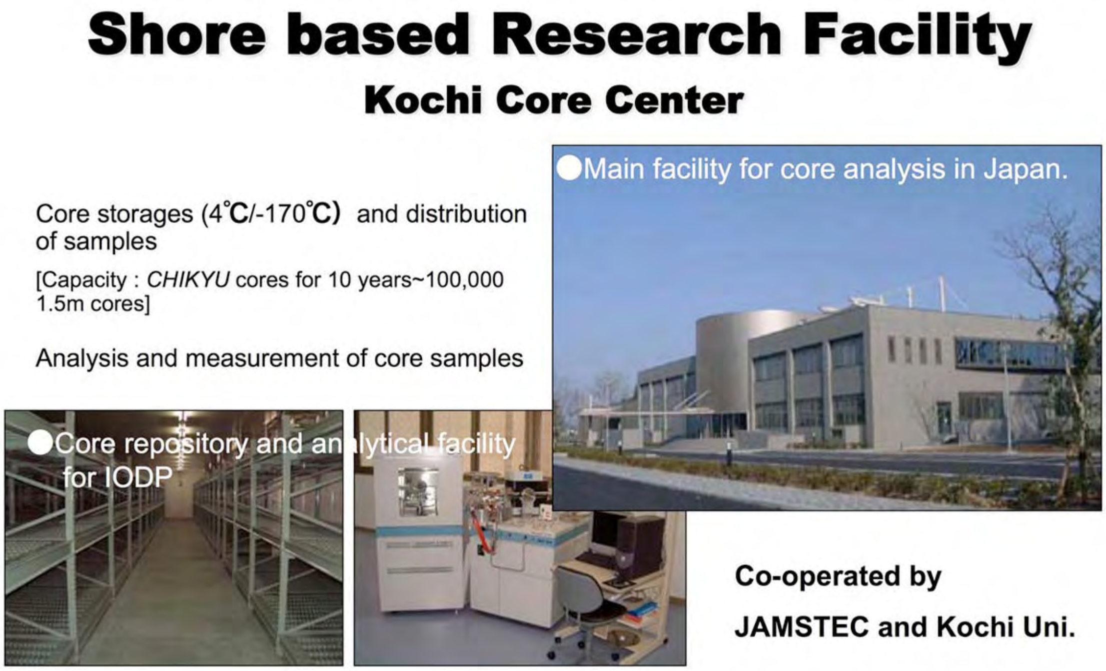


Moon pool
12 m x 22 m

Figure 5

Onboard equipment

Figure 6



Shore based Research Facility

Kochi Core Center

Core storages (4℃/-170℃) and distribution of samples

[Capacity : *CHIKYU* cores for 10 years~100,000 1.5m cores]

Analysis and measurement of core samples

● Main facility for core analysis in Japan.

● Core repository and analytical facility for IODP

Co-operated by JAMSTEC and Kochi Uni.

Toward a Comprehensive Understanding of the Nature of the Moho

Shoji Arai (Kanazawa University)
Report from Mohole Workshop in Japan

Mohole has two issues: one is to obtain the whole crustal section as a continuous drill core and the other is to drill through in-situ Moho. Both will provide us with innovative information if we prepare well. "Nature of the Moho" is a key to Mohole, and we should select the site for Mohole where we can resolve the question "What is the oceanic Moho?"

(1) Nature of the Moho

Moho is a discontinuity of Vp between around 7 km/sec above and around 8 km/sec below, being considered most typically as gabbro/peridotite boundaries. We can recognize the existence of the Moho from xenoliths. We obtain both peridotite/pyroxenite and gabbroic granulite xenoliths from continental or arc regions; the former and the latter are probably derived from the upper mantle and lower crust, respectively. Observations from ophiolites and limited exposures from the ocean floor suggest that boundaries between peridotites and layered gabbros may correspond to the oceanic Moho.

The Moho is, however, changeable along with modification of rock properties during geological processes. Successive igneous activity continuously changes deep parts of active arcs, where the Moho has been changing as well due to addition of new cumulates and restites and/or subtraction of materials by delamination. Cooling of hot plutonic rocks may promote a reaction, olivine + plagioclase = pyroxenes + spinel (troctolitic gabbros to spinel pyroxenites), may cause upward transformation of the initial Moho. Selective hydration and fracturing of the uppermost mantle may change its properties to be crust-like, resulting in the Moho modification.

(2) Nature of the oceanic Moho

The oceanic Moho may be variable depending on structure of the oceanic lithosphere, which is variable depending both on spreading rate and on distance from ridge-axis discontinuities. The oceanic lithosphere is composed of mafic igneous rocks, peridotites and their alteration products. Formation of the oceanic Moho is dependent on distribution of mafic and ultramafic rocks, thermal structure and degree of water circulation. If the Hess Model is applicable, the lowermost crust should be antigorite serpentinite. If the seismic discontinuity is a front of water circulation at lower temperatures (<500 to 600°C, lower than antigorite stability limit), chrysotile/lizardite serpentinite is possible as lower crust materials. Anyway, the oceanic Moho has never been correlated with petrological constitution.

(3) "Moho" observed in ophiolites

Typical ophiolites exhibit gabbro/peridotite (now serpentinized to various degree) boundaries, which may represent the Moho. In the Oman ophiolite, antigorite shows a very limited mode of occurrence, only associated with "diopsidite" of hydrothermal metasomatic origin. Serpentine in altered peridotite is generally chrysolite/lizardite. The Moho is not the serpentinization front but the gabbro/peridotite boundary in the Oman ophiolite.

There are at least two kinds of gabbro/peridotite contact (Moho) in the Oman ophiolite: "gabbro-in-dunite" Moho and "dunite-in-gabbro" Moho. The former is characterized by gradual change from underlying dunite (Moho-transition zone dunite) to layered gabbro with an upward increase of frequency of gabbro bands (sill-like intrusions) in the dunite. This may have been formed at a spreading ridge and is primary. The latter is characterized by a secondary gabbro/dunite contact, which was made by intrusion of dunite (late-intrusive dunite) to gabbro. Nature of the late-intrusive dunite is problematic: if it is a mid-ocean ridge product, we can expect two kinds of Moho from the present-day ocean floor. If it is of arc origin, we should examine only the "gabbro-in-dunite" Moho for probing oceanic lithosphere. If it is related with backarc-basin basalt, we should reconsider the origin of the Oman ophiolite.

There could be a "counterfeit Moho" in some ophiolites. The Horokanai ophiolite, Hokkaido, Japan, has a crustal section of MORB affinity and a mantle section of highly depleted character. The Horokanai ophiolite is possibly a collage of crustal and mantle sections from different ophiolites; the apparent Moho was formed during formation of the Horokanai ophiolite. Ophiolite is useful as an analogue of oceanic lithosphere, but care should be taken when combined with Mohole.

(4) Strategy

1. Pre-Mohole on the Oman ophiolite

We would like to propose a "Pre-Mohole" on the Oman ophiolite. One of its items is to propose to systematically determine physical properties of rocks that are altered to various extents and are mixed with varying proportions. It will facilitate our construction of petrologic model using physical (seismic) properties of oceanic lithosphere. This is indispensable to successful preparation operation for Mohole. We can also conduct seismic experiments to determine velocity structure of the ophiolite, where surface geology has been well known. They will be combined with continental drilling.

Detailed seismic structure has been determined in IBM (Izu-Bonin-Mariana arc) and surrounding area by a JAMSTEC group. Combined with a petrologic model of IBM crust-mantle formation, we can establish nature and origin of the Moho at an oceanic island arc system.

For the first phase of Mohole (at <2500 m water depth), we propose drilling on Lau Basin, one of the backarc basins. The Sea of Japan, which is composed of an ocean basin and rifted/stretched continental lithosphere and can provide us with unrivaled information, is also a candidate for this phase of Mohole.

For the second phase of Mohole (at <4000 m water depth), some place can be selected at the equatorial EPR, where active and fossil spreading ridges are available. Drilling on the ocean lithosphere of fast-spreading ridge origin is unparalleled as a "standard oceanic curst-mantle".

If we can accomplish a series of project proposed above, we can proceed to the comprehensive understanding of the nature of the Moho, the shallowest important discontinuity of the Earth, at various tectonic settings.

On the Outcomes of the ODP "Architecture of the Oceanic Lithosphere" Program Planning Group

Mathilde Cannat (IPGP)

In 1998 SCICOM commissioned a PPG to « develop a plan to study ridge-crest processes and the architecture of the oceanic lithosphere ». SCICOM further indicated that this plan « should include, but not be limited to, a complete penetration of the oceanic crust, and should be linked to the establishment of long-term seafloor observatories at ridge axes and in older crust off-axis ».

The PPG (Rodey Batiza -co-Chair, Joe Cann -co-Chair, Mathilde Cannat, Don Forsyth, Jeff Gee, Kathy Gillis, Ingo Grevemeyer, Peter Kelemen, Graham Kent, Eiichi Kikawa, Charles Langmuir, Rolf Pedersen, Philippe Pezard) met twice, in May 1998 at Scripps in San Diego, and in December, 1998 over the San Francisco AGU. It submitted a very short final report early in 1999, listing the scientific questions seen as key to understanding the architecture of oceanic crust at fast and slow spreading rates, and outlining a drilling strategy for the 1999-2003 (end of the Ocean Drilling Program) period.

This drilling strategy was directly based on proposals or pre-proposals that were in the system at the time, while the selection of key scientific questions was inspired by the outcomes of previous meetings and workshops, the latest in date at that time being the workshop on « Scientific drilling into the 21st century », held in Woods Hole in 1996.

The proposed drilling strategy called for a total of 5-6 legs before 2003, with two priorities :

1. Start a multi-leg program for complete penetration of intact fast-spread crust (2 Legs before 2003)
2. Conduct offset drilling (3-4 Legs before 2003) of lower crust and mantle rocks in a variety of settings (detachment faults at slow ridges, Site 735B at the Southwest Indian Ridge, ultramafic outcrops at 15°N on the Mid-Atlantic Ridge, and exposed fast-spread EPR crust at Hess Deep).

Over its short period of activity, the PPG also took a quite proactive approach to help the proponents of the 10 existing relevant proposals improve their projects and meet the requirements of the review and site survey panels. This probably was helpful… in any case a good part of the PPG's drilling plan was actually carried out over the last 3 years of ODP, and the first 2 years of IODP : 2 legs on fast spread crust at Site 1256, and 3 offset drilling legs (15°N and 2 legs at the Atlantis core complex in the Atlantic).

The PPG's most effective action in terms of defining a drilling strategy was to closely examine the criteria for choosing a site for an intact section of ocean crust, then to carefully review possible sites against these criteria. This was achieved during the first meeting, with the outcome that the ultra-fast Guatemala basin target of Proposal 522 (now the location of Site 1256) was collectively recognized as a good choice, meeting all essential criteria but one (crust there was formed at low latitudes, a major problem for paleomagnetic studies). A potential site about 300 nm west of Baja California was also tentatively identified with the help of P. Lonsdale. The PPG recommended that this site be added to the seismic survey then planned in the Guatemala basin in preparation for proposal 552.

The PPG then proceeded to make specific recommendations for the drilling strategy at the complete crustal penetration site. In the following paragraphs, I've simply pasted the relevant sections of the PPG's report, adding only short comments as needed to replace this report into context.

The criteria for choosing a site for an intact section of ocean crust were listed as follows :
Essential Criteria :
1. Fast-spreading (>100 mm/yr full rate)
2. Age of crust >10 Ma
3. >50-100m of sediment
4. Water depth < 4000m
5. Simple tectonic setting
6. Clear 2A/2B and Moho seismic boundaries from seismic studies
7. Relatively fast layer 2A velocities and minimal low velocity surface layer
8. Crustal thickness between 5-6 km
9. Formation at a latitude >15° N or S
10. Present location <30° latitude
11. Within a reasonable distance to adequate port facilities
12. Adequate site surveys especially including magnetics and detailed seismic studies

Rationale: A total crustal penetration in fast vs. slow-spread crust is desirable because of the apparent geologic simplicity of fast-Vs. slow-spread crust and because fast-spread crust is thought to be representative of the largest amount of present-day ocean crust. Choosing relatively old, cold and thickly sedimented crust is important to maximize the chances of hydrothermal sealing of the upper crust, with improved drillability and core recovery, and to minimize the difficulties of high temperatures in the hole. These requirements play off against the need for modest water depths to reach deeper crustal levels with the Joides Resolution. Formation at a magnetic latitude >15° is important because good signals of magnetic inclination are needed to detect the possible rotation of crustal blocks. In addition, magnetic inclination changes can provide evidence of the original dips of lava flows, with important implications for inferring the original geometry of eruptive conduits, flow runout distances, and other variables. In order that the site can be drilled during a multi-leg program, it is important that the site have good weather year around and be close to ports to minimize losses to transit. An adequate site survey is especially important, including detailed seismic studies in excess of the minimal ODP requirements. These are essential to ensure normal crustal thickness, to avoid local tectonic complications like OSCs and other small offsets, and to pick sites with enhanced drillability (i.e. thin or absent upper rubble layer; low porosity in layer 2A).

In addition to the 12 essential criteria above, the PPG listed the following 4 desirable criteria:
1. Super-fast spreading (>130-150 mm/yr full rate)
2. Age of crust 20-30 Ma (but generally conflicts with 4 and 5 above)
3. >200m of overlying sediment
4. Near a deep-sea cable and/or flank observatory
5. Within an ION/OSN tile indicating a gap in global seismic coverage

Rationale: Super-fast spreading is desirable because such crust is apparently tectonically simpler than fast-spread crust and because available data indicates that the depth to the AMC, and thus perhaps layer 2B thickness, is systematically smaller at super-fast rates. Location of the site near cables and observatories is also highly desirable, and if so, then it would be desirable to case as many as possible of the pilot holes drilled prior to starting the deep hole. Having several cased holes is important for wireline reentry to deploy and recover borehole instrument packages, and for doing cross-hole experiments in an observatory environment.

The PPG then proceeded to examine 4 fast-spread potential sites against the above criteria.

The PPG considered three sites at the meeting, however none of them met all the "essential" criteria. For this reason, a fourth site was found after the meeting. The four sites are: 1) The Hawaii-2 Observatory (H2O) site (proposal 500-Full2), 2) a site in the equatorial Pacific (proposal 499-Rev), which we call the ION/OSN site, 3) A site in the Guatemala basin (EEQ-2, Leg 138- proposal 522-Pre), and 4) a site about 300 nm west of Baja California. The H2O site is too deep (~4500m) and is relatively remote. In addition, the sediment cover is thin (50-75m). The ION/OSN site is also relatively far from ports and was formed at an unfavorable magnetic latitude. The Guatemala basin site meets all the essential criteria except for appropriate magnetic latitude, and meets two of the desirable criteria. a site about 300 nm west of Baja California was identified. This site formed at superfast spreading rate (~130 mm/yr), has at least 150m of sediment, is in 3800m water depth and formed at a latitude of 15°N or greater. The Baja site formed at superfast spreading rate (~130 mm/yr), has at least 150m of sediment, is in 3800m water depth and formed at a latitude of 15°N or greater. This site appears very promising, however there is not yet an adequate seismic study upon which to identify a site with appropriate crustal thickness, away from OSCs, clear 2A/2B boundary, and high velocity layer 2A (essential criteria 5-8). A detailed site survey is also needed to obtain shallow velocity structure in order to pick pilot hole sites with as thin as possible or absent upper rubble layers. The PPG has encouraged Doug Wilson and his collaborators for Proposal 552 to incorporate a site survey of the Baja site in their field program to survey the Guatemala basin site.

Having discussed the criteria for choosing the total crustal penetration site, the PPG then had quite a thorough discussion, including input from TAMU engineers, of what would be the best drilling strategy to efficiently prepare for full crustal penetration at the chosen site.

In order to achieve complete crustal penetration of fast-spread crust after 2003, we envision a general strategy as follows:

a) Conduct site surveys

b) Identify the best site

c) Conduct a Leg of drilling to drill one to three pilot holes, the best of which would be planned as the deep hole. The goal of the first Leg would be to have the designated hole drilled and cased to 300-500m with large-diameter (20") casing.

d) Additional Legs of drilling to deepen the hole to ~3000-3500m. Leg 2 would drill and case (13 3/8") to ~1500m, and would investigate the layer 2A/2B boundary, the layer 2/3 boundary, and the top of the gabbro section; Leg 3 would drill and case (10 3/8") to ~3000m, and Leg 4 would drill ahead as far as possible without casing.

e) If possible, deepen the hole with riser-capable platform. Alternatively, drill a new hole nearly and case to full depth, with continued drilling to Moho with additional legs in the post 2003 period.

Rationale for Deep Drilling Through the Ocean Crust to the Moho

Peter Kelemen

13:30 Mission Moho, updating our vision for ocean lithosphere drilling

You are scheduled for 30 minutes …

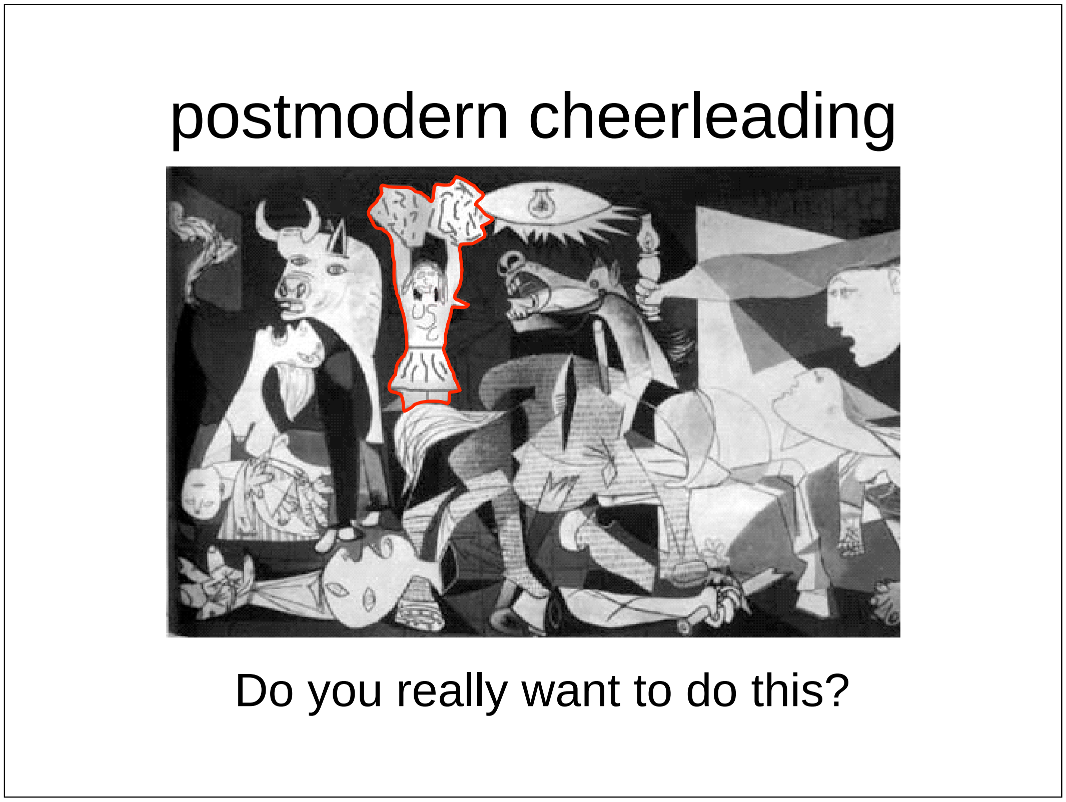
dress code:
visionary cheerleader.

Time limits will be enforced by firehose.

60 slides in this
new, improved version!

(that's what happens to visionary cheerleaders)

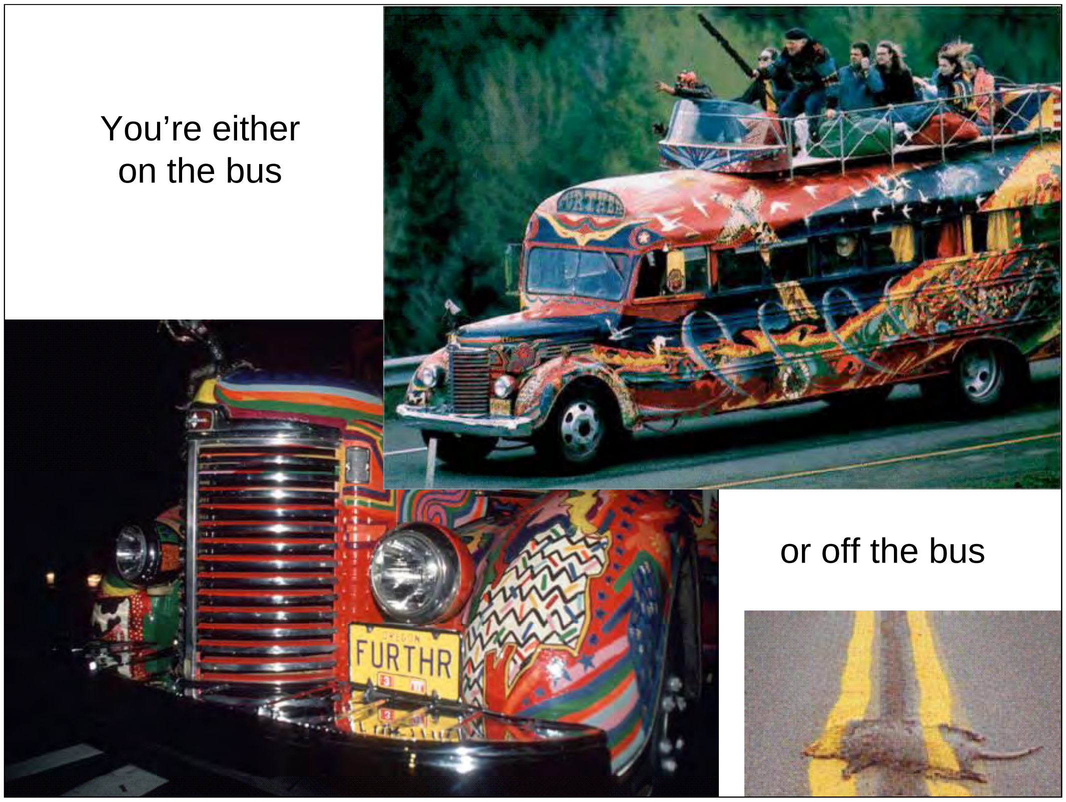
Excerpts from email to me from Dave Christie. Thanks, Dave, I was genuinely inspired.



postmodern cheerleading

Do you really want to do this?

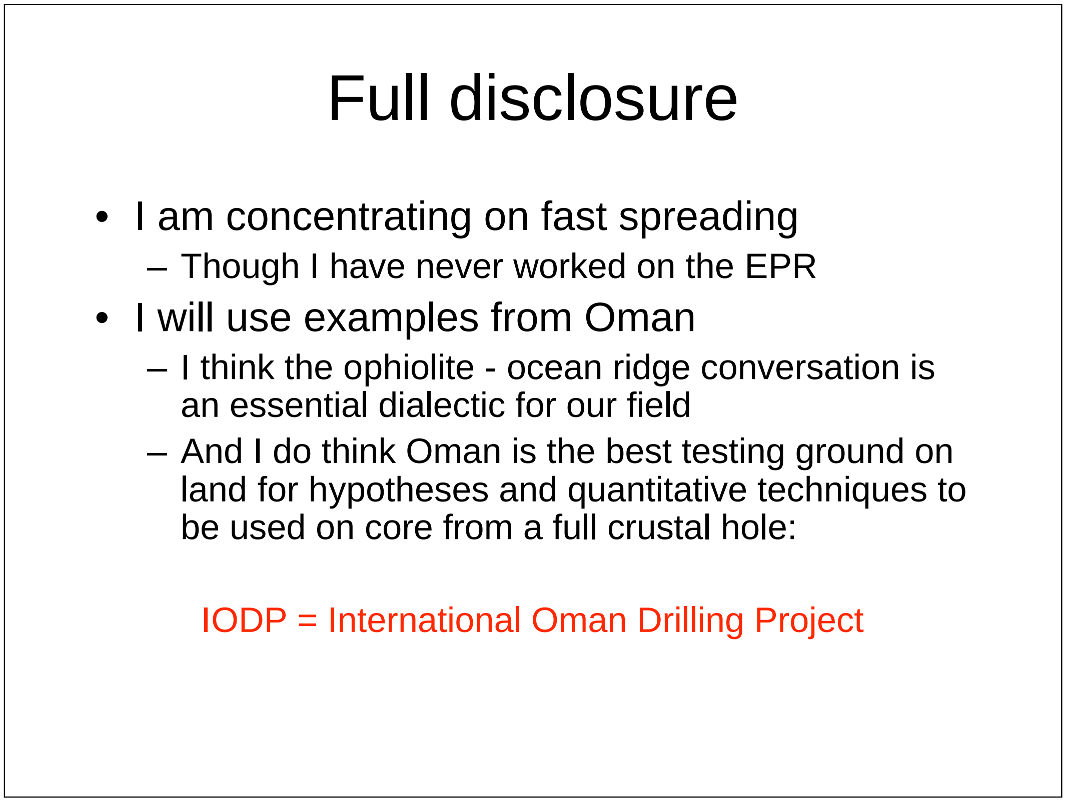
Before I found this illustration, I already was looking for something to use to illustrate the concept of a “postmodern cheerleader”, to emphasize that our community will need honesty, irony, and nerves of steel to pursue Mission Moho in the midst of the oil endgame, the War on Terra, global warming, horrendous poverty, and an AIDS epidemic. This picture is perfect for my purpose.



You're either
on the bus

or off the bus

As a devote of Ken Kesey and Tom Wolfe, I knew I could find pictures of "The Bus" to go with the famous quote. I am a geologist, and I kind of prefer to work on projects in small groups. As a result, in the context of Mission Moho, most likely that will be me in the lower righthand corner. However, my goal in coming to the meeting was to persuade the participants to GET ON THE BUS. A full crustal hole is now possible, but only if the community pulls together and speaks with one voice. There will be setbacks, but we will need to agree in advance that it is worthwhile to persevere, and to commit the necessary resources to completing this project. In the end, everyone will benefit from the data and also from the increased public awareness of the science surrounding this great achievement.

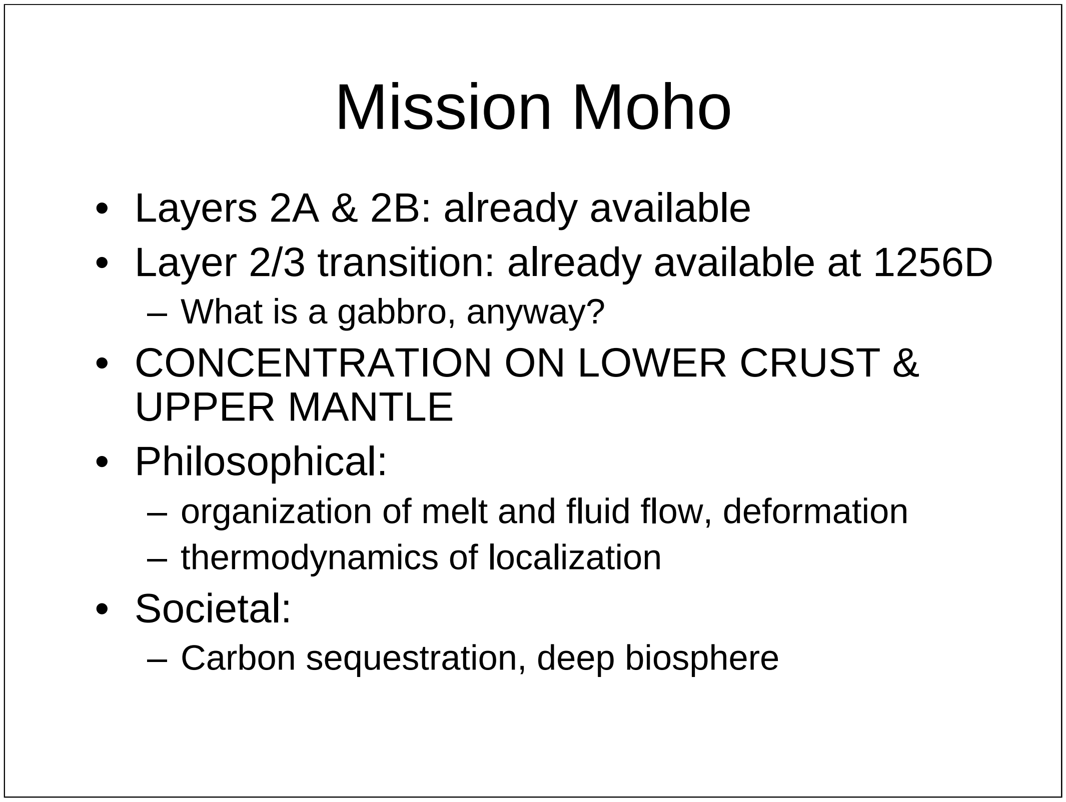


Full disclosure

- I am concentrating on fast spreading
  - Though I have never worked on the EPR
- I will use examples from Oman
  - I think the ophiolite - ocean ridge conversation is an essential dialectic for our field
  - And I do think Oman is the best testing ground on land for hypotheses and quantitative techniques to be used on core from a full crustal hole:

IODP = International Oman Drilling Project

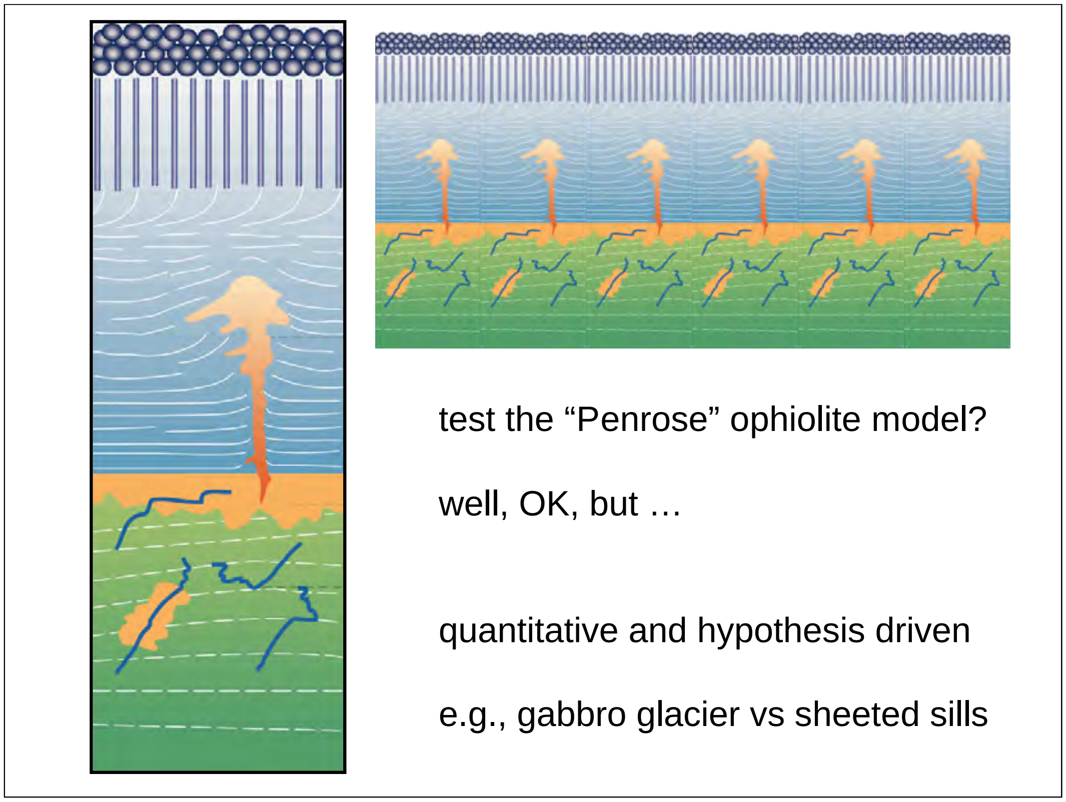
Full disclosure



Mission Moho

- Layers 2A & 2B: already available
- Layer 2/3 transition: already available at 1256D
  - What is a gabbro, anyway?
- CONCENTRATION ON LOWER CRUST & UPPER MANTLE
- Philosophical:
  - organization of melt and fluid flow, deformation
  - thermodynamics of localization
- Societal:
  - Carbon sequestration, deep biosphere

Self-evident



test the “Penrose” ophiolite model?

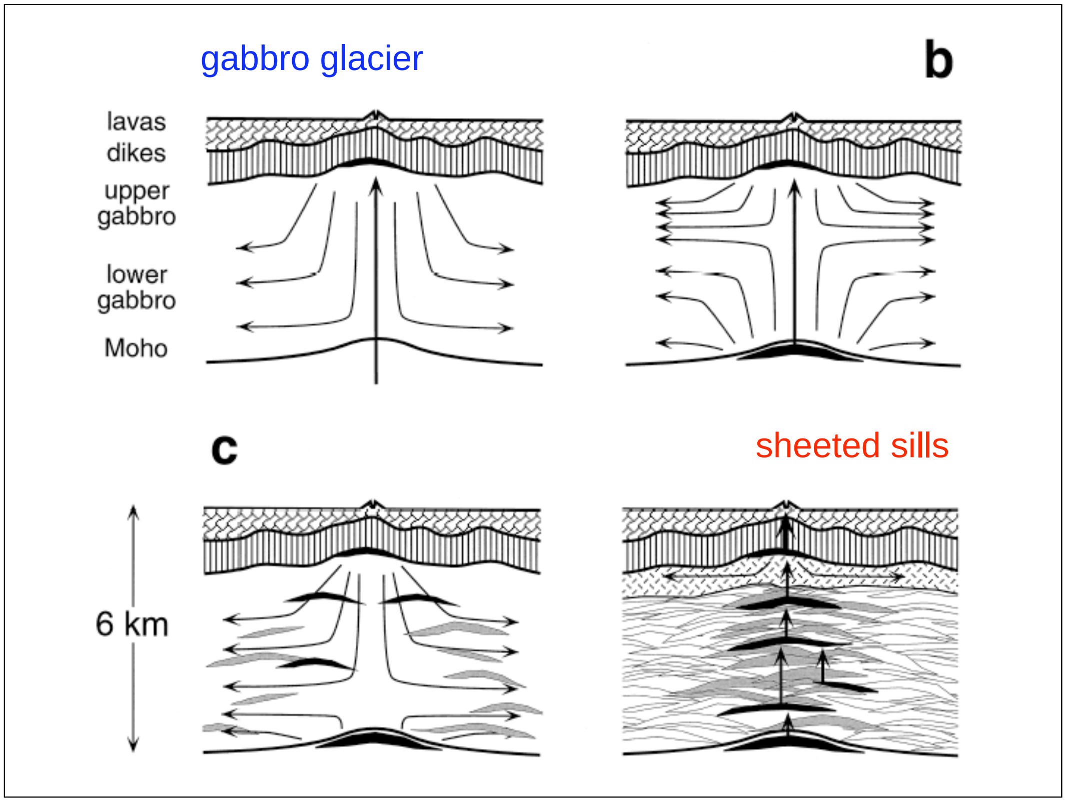
well, OK, but …

quantitative and hypothesis driven

e.g., gabbro glacier vs sheeted sills

I personally think that the relatively uniform veneer of pillow basalt at the top of Pacific basement is underlain by a relatively uniform layered crust much like the “Penrose ophiolite” outlined by Bob Coleman and others many, years ago. I think that most members of our community would agree, if they were really honest with themselves and others. Of course, we could be surprised and that would be great. But we don’t want to create a straw man, when most people believe - for pretty good reasons - that we already know the answer.

There are many fundamental questions to which we don’t know the answer, and which can be addressed by quantitative work on (nearly) complete core through the oceanic crust and into the shallow mantle.



One unresolved question is the mode of igneous accretion of the lower oceanic crust at fast-spreading ridges. This schematic diagram illustrates two proposed end-member hypotheses, and some intermediate possibilities. In the “gabbro glacier” model, the entire lower crust forms via crystallization in a single, shallow melt lens, followed by ductile flow downward and outward. In the “sheeted sills” model, gabbroic rocks of the lower crust crystallize from many small sills at their current depth of emplacement in the crust. There are many intermediate possibilities.

Figure from Korenaga & Kelemen, EPSL 1998. Gabbro glacier idea outlined by Sleep JGR 1975; Dewey & Kidd GSA Bull 1977; Nicolas et al. Geology, ; Quick & Denlinger, first in their computer program “gabbro glacier”, distributed widely in 1992, and then in JGR, 1993; Phipps Morgan & Chen, JGR 1993; and Henstock et al., JGR 1993. Idea that some layers in layered intrusions & ophiolites form from sills was outlined by Browning Geol Soc Lond 1984; Bédard et al. J Geol Soc Lond 1988. Idea that this forms fast-spreading oceanic crust proposed by Kelemen et al., EPSL 1997; Korenaga & Kelemen, JGR 1997, EPSL; Kelemen & Aharonov, AGU Monograph 1998; Korenaga & Kelemen EPSL 1998.

gabbro glacier requires increasing shear strain near the base

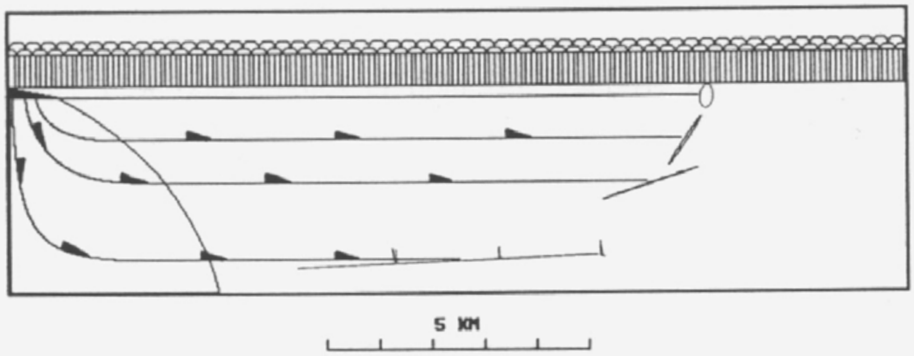
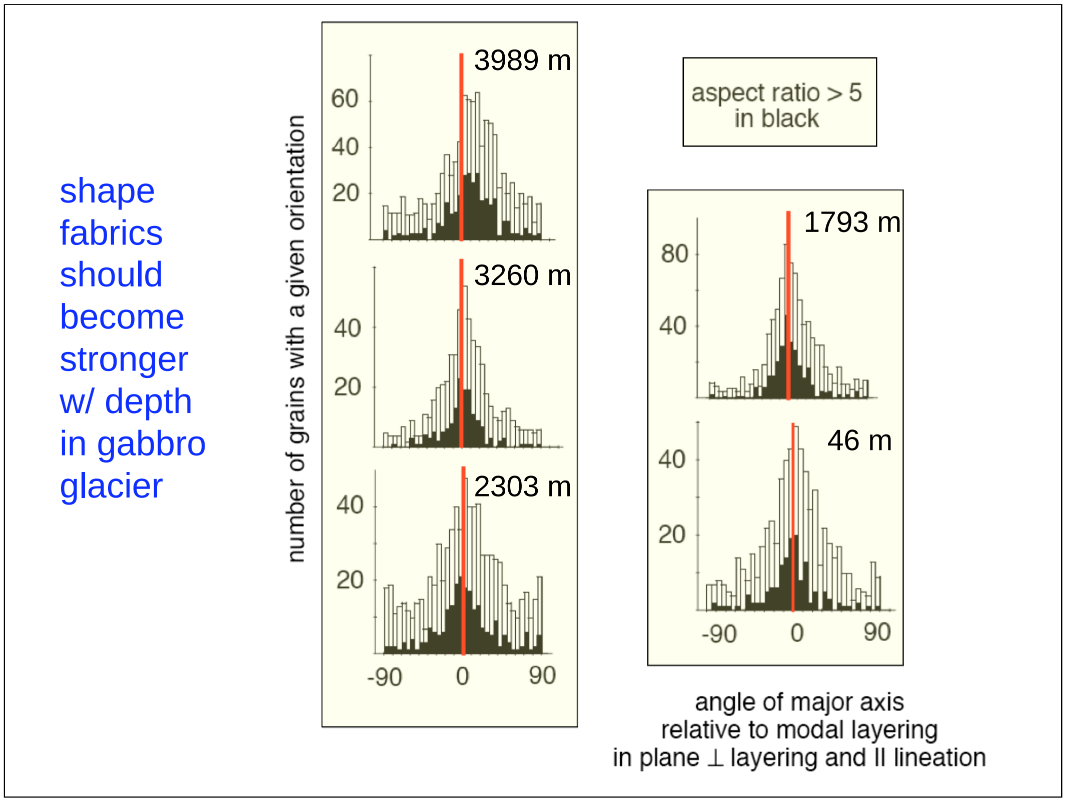


Fig. 7. Strain ellipses generated by integration of deformation during flow originating at different positions on the magma chamber floor. Trajectories indicated by lines with arrows. Final shape of ellipse shown at end of each trajectory. Material deposited near the ridge axis is highly sheared as it follows a trajectory that passes near the Moho. Material deposited farther from the ridge axis experiences less deformation and is incorporated into higher levels of the crust. Symbols are as in Figure 6. Horizontal and vertical scales are equal.

Figure from Quick & Denlinger JGR 1993, showing strain ellipses for gabbro glacier, with dramatically increasing shear strain as a function of depth. There is a similar figure in Phipps Morgan & Chen JGR 1993. This shear strain gradient should be recorded in mineral shape fabrics (lineation, foliation) IF the rocks have non undergone post-kinematic recrystallization, and in mineral lattice fabrics EVEN IF the rocks have undergone post-kinematic recrystallization. A drill hole through the lower oceanic crust, with reasonable recovery of oriented core, could resolve this question via detailed studies of crystal sizes, shapes and lattice fabrics.



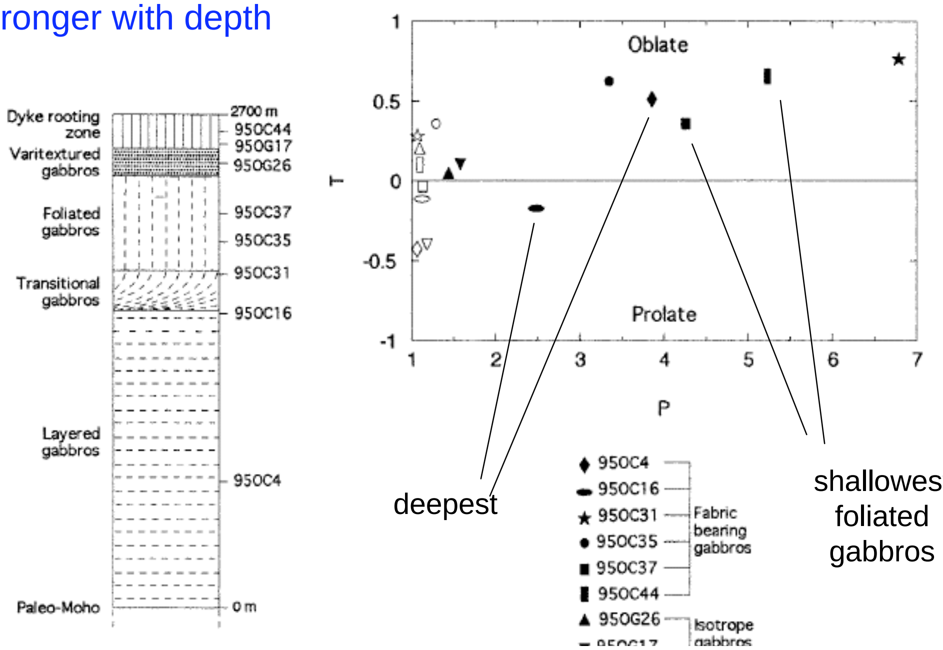
shape fabrics should become stronger w/ depth in gabbro glacier

Unpublished data set, based on crystal size studies of Garrido et al., G-cubed 2001, illustrating the aspect ratio and plunge of the major axis on plagioclase elongation in sections perpendicular to layering, and parallel to lineation. Heights in the upper right corner of each panel are heights above the crust-mantle transition zone (MTZ), and panels are arranged in order of increasing depth (decreasing distance to MTZ) from top to bottom and left to right. This data set does not show any increase in the strength of foliation with increasing depth in the lower crust, as predicted by the gabbro glacier hypothesis. If anything, the slight obliquity of the plagioclase shape fabric relative to the plane of layering in the shallowest sample (3989 m) indicates a stronger deformation fabric in that sample.

HOWEVER, (1) this is a very limited data set, (2) a shape fabric could have been obscured or eliminated during post-kinematic recrystallization, particularly for slowly cooled rocks near the base of the crust, and (3) the spreading rate during formation of the Oman ophiolite is not known. Over 300 km along strike in the Oman ophiolite, there are few if any places where mantle peridotite was exposed on the seafloor, whereas peridotite exposures along fracture zones and normal faults is common along slow spreading ridges, so most workers infer that the Oman ophiolite formed at fast- to intermediate spreading rates. However, the remaining uncertainty about the spreading rate is important, as thermal models and thus crustal accretion models vary dramatically over the range of fast to intermediate spreading rate.

in gabbro glacier, lattice fabric should become stronger with depth

weak <= fabric => strong

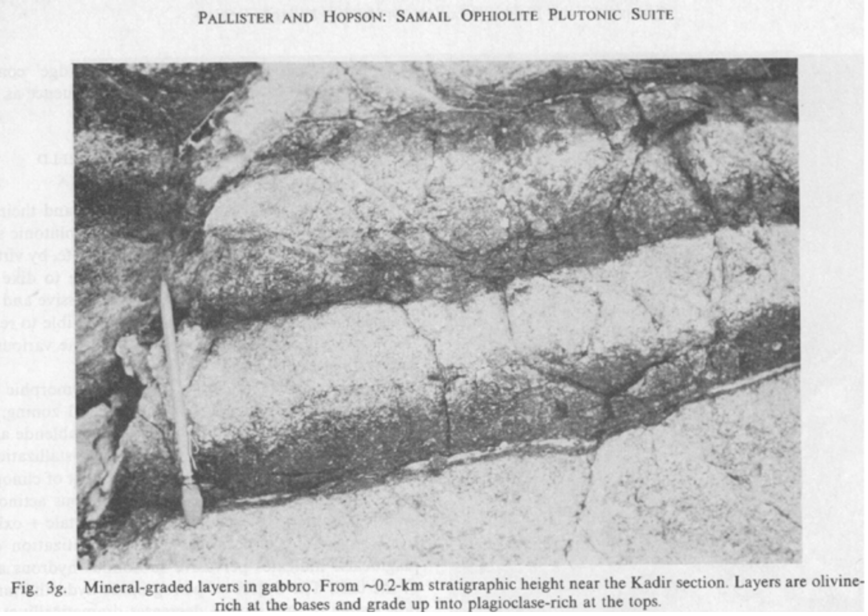


deepest

shallowest foliated gabbros

Data from Yaouancq & MacLeod, MGR 2000, on plagioclase lattice preferred orientation (LPO, lattice fabric) in samples from a crustal section of the Oman ophiolite. The gabbro glacier model predicts that there should be a strong gradient in the strength of the fabric (P axis value) with increasing depth in the crust. Such a gradient would not be obscured by post-kinematic recrystallization, as growing plagioclase grains would inherit the kinematic LPO. A gradient in the strength of the LPO with depth is not present in the Yaouancq and MacLeod data. However, the data come from a very limited number of samples, and samples from near the MTZ, where the gradient should be best developed, are absent. In addition, as noted in the previous caption, the spreading rate of the Oman ophiolite could have been intermediate to fast, and substantial variation in the processes of crustal accretion are predicted over this range of spreading rates. Studies of the LPO in core from the lower oceanic crust, formed at a known, fast spreading rate, would provide a definitive constraint on the processes of crustal accretion at fast spreading ridges. Fast spreading have formed most of the Earth’s oceanic crust.

maybe some layering structures near the base of the crust are not consistent with large shear strains

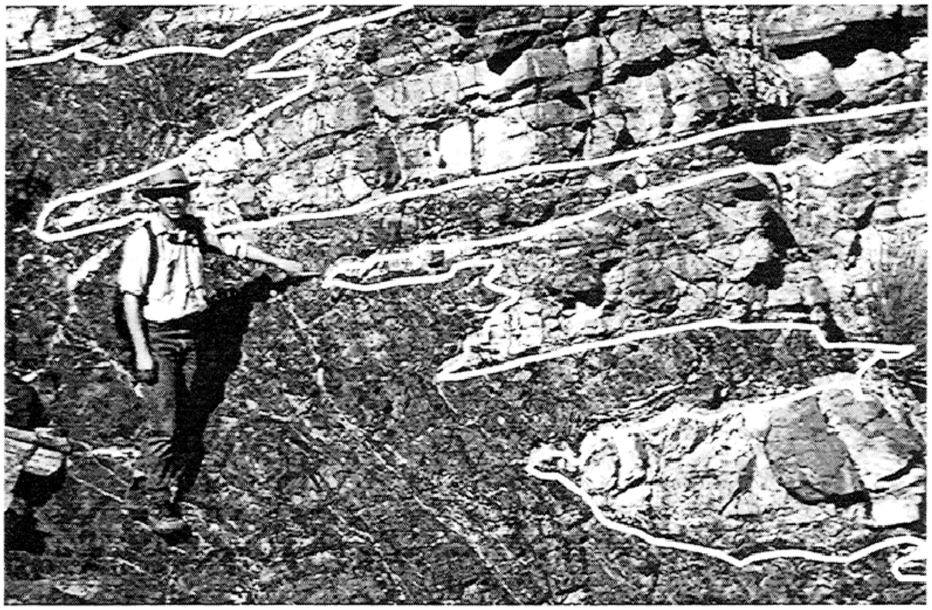


PALLISTER AND HOPSON: SAMAIL OPHIOLITE PLUTONIC SUITE

Fig. 3g. Mineral-graded layers in gabbro. From ~0.2-km stratigraphic height near the Kadir section. Layers are olivine-rich at the bases and grade up into plagioclase-rich at the tops.

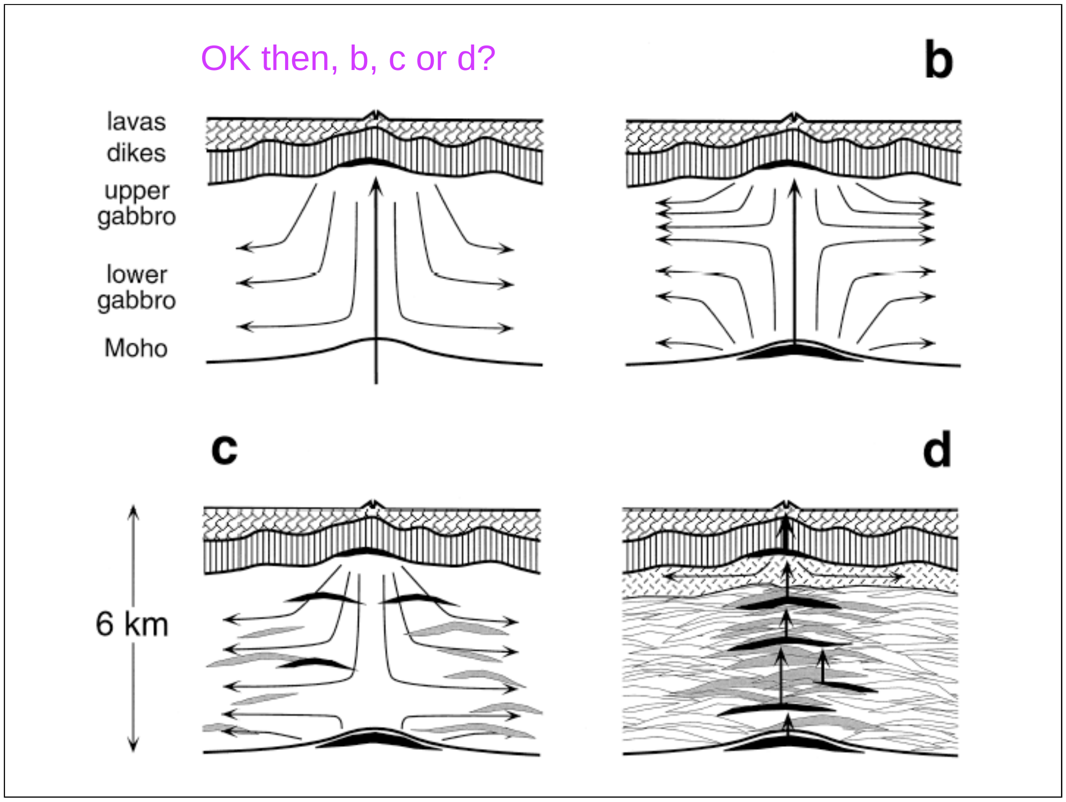
Figure from Pallister & Hopson, JGR 1981, illustrating fine scale, graded layering, as observed in the lower crust of the Oman ophiolite, would not be preserved at large shear strains. Thus, most field geologists agree that rocks with such fine-scale layering were not deformed in a gabbro glacier.

some layered gabbros, similar to lower crust and complementary to sheeted dikes & lavas, intruded into peridotite below the Moho



These lenses of layered, gabbroic rocks formed within peridotites in and below the MTZ in the Oman ophiolite. Thus, they did not form by crystallization in a shallow melt lens followed by flow downward and outward to form the oceanic lower crust. Minerals in these MTZ gabbro lenses are in equilibrium with the magmas that formed sheeted dikes and lavas in the ophiolite. Given that the sheeted dikes certainly formed at a spreading center, we infer that the gabbro lenses in the MTZ also formed at a spreading center, and not “off axis”. Again, this type of evidence indicates that some rocks in the Oman lower crust and uppermost mantle did not form via a “gabbro glacier”. However, we don’t know the Oman spreading rate. Will similar gabbroic lenses be recovered from the Pacific MTZ? Or not?

Figure from Korenaga & Kelemen, JGR 1997



OK then, b, c or d?

We’ve established that some rocks in the Oman ophiolite did not form via a gabbro glacier process, from a single shallow melt lens. However, there are several intermediate possibilities involving ductile flow of gabbros from a few melt lenses, and/or intrusion of sills into a gabbro glacier, in addition to the simple, sheeted sill end-member in which all plutonic rocks crystallized at their future depth in the crust.

magma lens size can be determined with chemical layering

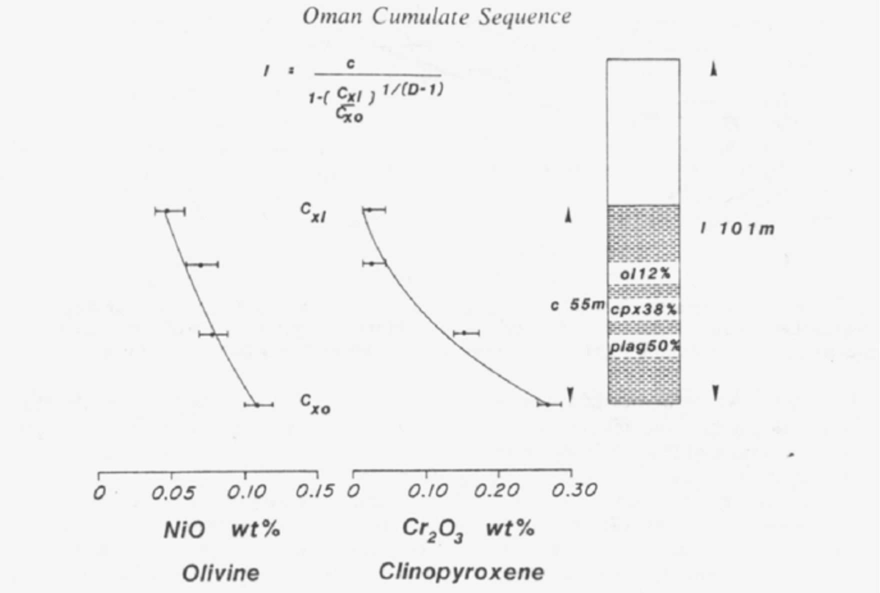
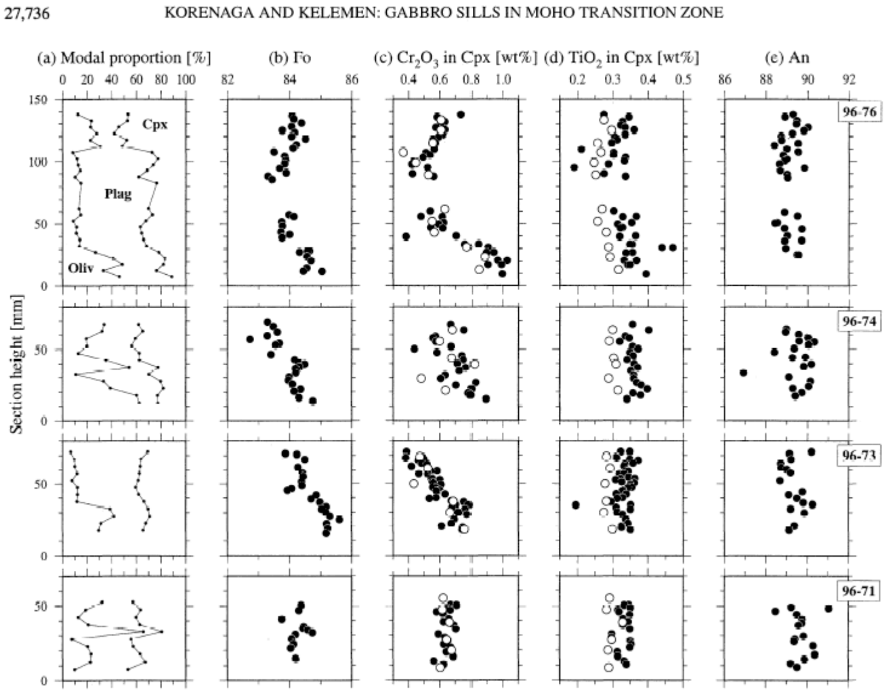


FIG. 4. Calculation of liquid-column height. Data for cycle Ib are shown. For derivation of expression see text.

In order to constrain the size of the magma bodies that form the crust, one can use chemical layering. Where a continuous variation in "compatible element" concentration occurs over some well defined height in a gabbroic section, one can estimate the mass ratio, and thus the height, of the original melt to the observed crystals. Compatible elements are those which are partitioned preferentially into crystals relative to liquids. Here, in an illustration involving samples from the Oman ophiolite, a 55 m sequence of lower crustal gabbros shows continuously decreasing Nickel in olivine and Chromium in clinopyroxene with increasing height. Simple mass balance indicates that this column of rock crystallized from a magma mass roughly twice the mass of the observed gabbro sequence, or a "melt column" ~ 100 meters thick.

Figure from Browning, J Geol Soc Lond 1984.

some magma lenses ~ 1 to 10 m

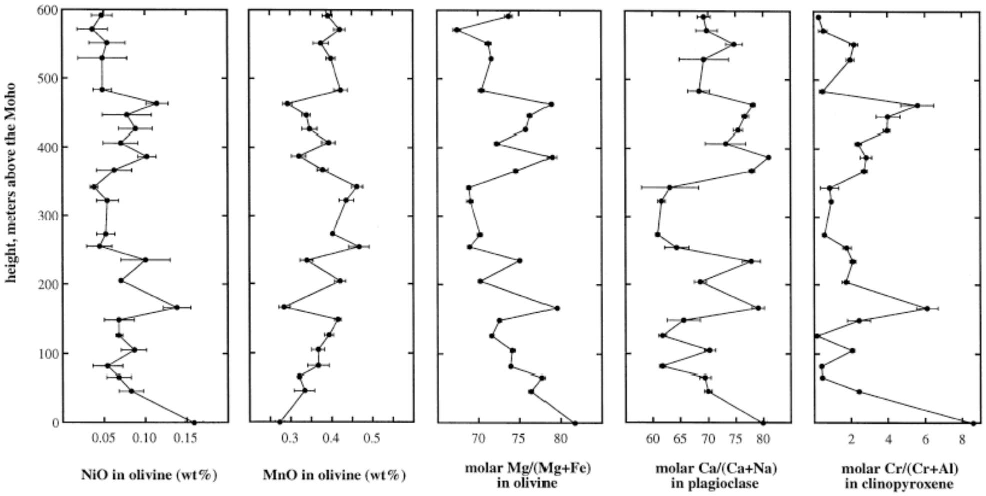


Data from gabbro lenses in the Oman ophiolite MTZ (illustrated in a previous slide). Here, variation in the forsterite content of olivine (Fo, or molar Mg/(Mg+Fe)) and Chromium in clinopyroxene takes place in continuous sequences that are just a few centimeters in height, indicating that the rocks crystallized in a "melt column" just a few meters tall. Perhaps, these rocks have been thinned during ductile deformation, but even 10:1 shear strains yield the result that melt columns were a few tens of meters in height.

Figure from Korenaga & Kelemen, JGR 1997.

chemical layering puts constraints on melt migration

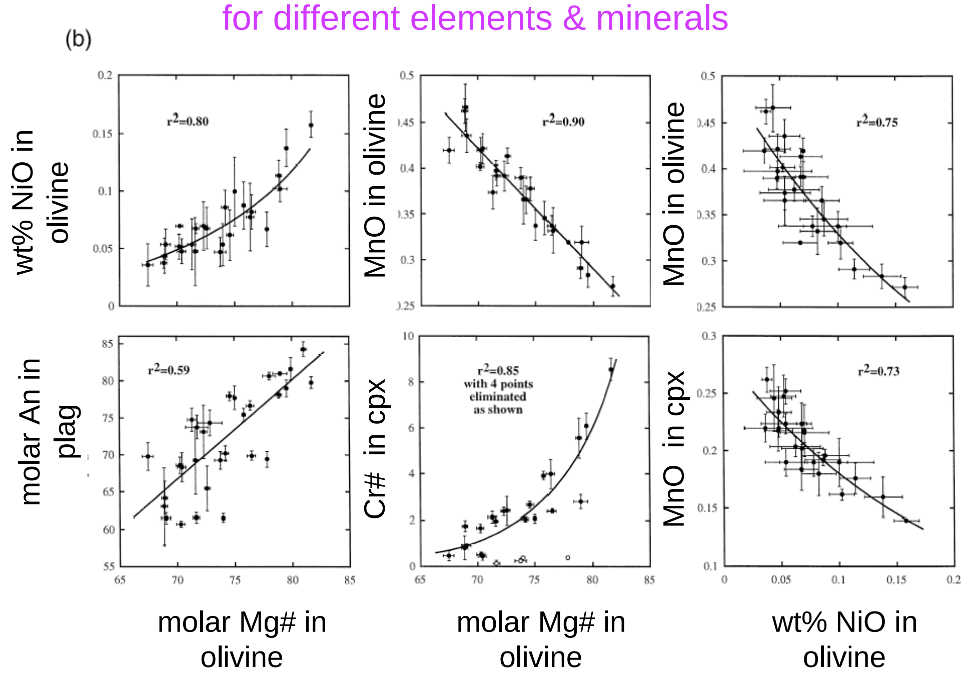
J. Korenaga, P.B. Kelemen / Earth and Planetary Science Letters 156 (1998) 1–11



chemical layering in Oman not well correlated w/ depth

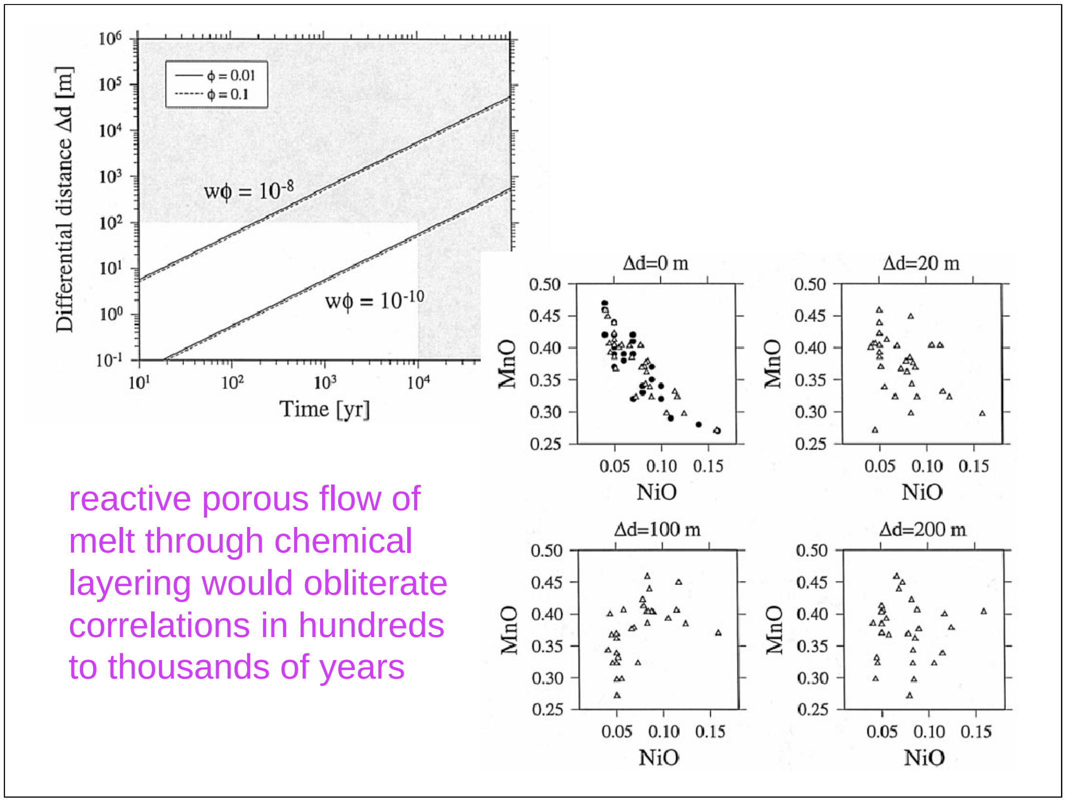
Chemical layering in gabbroic rocks can also be used to constrain the processes of melt transport through the oceanic lower crust. The next few slides illustrate a case study from a lower crustal section in the Oman ophiolite, in which Korenaga & Kelemen (EPSL 1998) used data from the PhD thesis of Paul Browning (Open University, UK, 1982). Here we see data on mineral composition versus height above the MTZ. Two things to note are that there is little if any correlation of mineral composition with height, and that almost every data point forms an inflection, so the actual scale of vertical variation in composition is not known, but is less than the sample spacing.

chemical layering well correlated
for different elements & minerals



Despite the lack of correlation of mineral composition with height in the data in the previous slide, there is a good correlation between the compositions of different minerals. This is important, because these correlations involve both compatible elements, which are strongly partitioned into the solid phases, and incompatible elements which are partitioned into coexisting liquid. Migrating melt passing by equilibrated porous flow through gabbroic rocks would dominate the mass balance for the incompatible elements, and would "impose" a melt signature on the minerals, whereas the rocks would dominate the mass balance for compatible elements and would "impose" concentrations in the melt that are in equilibrium with the original mineral compositions for these elements.

Figure from Korenaga & Kelemen, EPSL 1998



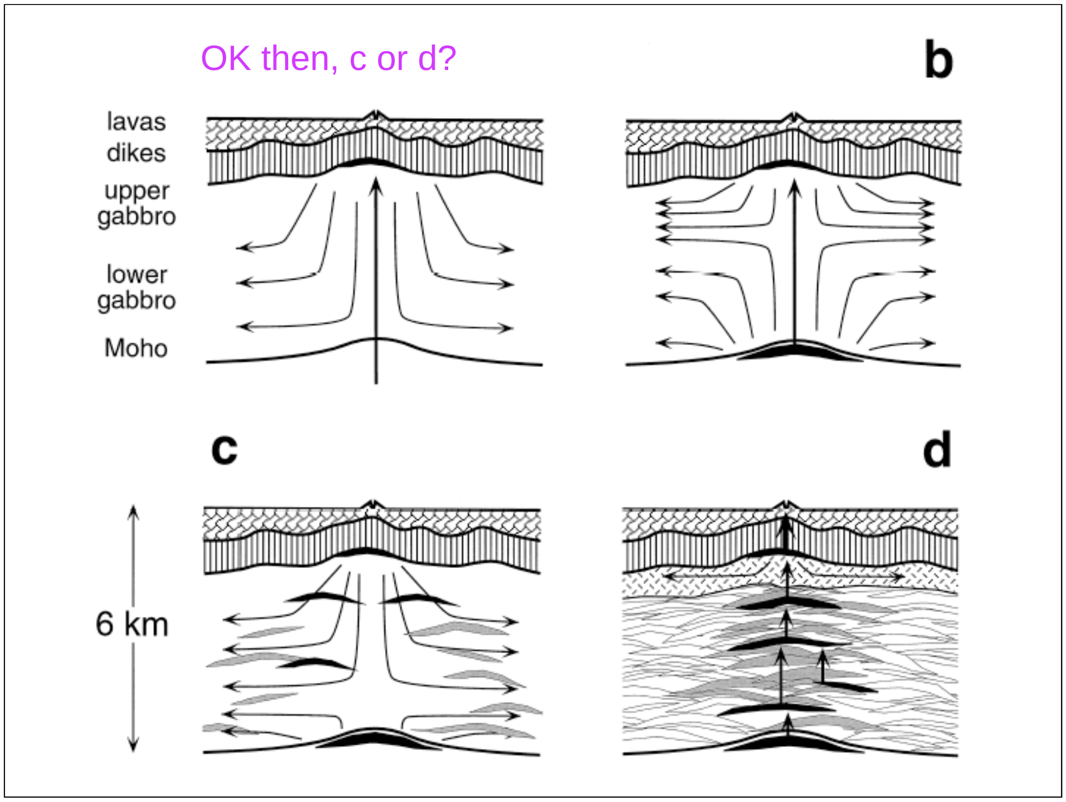
reactive porous flow of melt through chemical layering would obliterate correlations in hundreds to thousands of years

Here, we see the result of calculations involving diffuse porous flow of reactive melt through gabbroic rocks. The initial chemical layering looks like the data from Paul Browning’s thesis (previous two slides), with a correlation between NiO and MnO in olivine as shown in the panel labelled “delta d = 0 m”. As a result of porous flow through this chemical structure, incompatible MnO moves with the liquid, while compatible NiO stays in one place. This destroys the observed correlation between MnO and NiO in olivine after a few hundred to a few thousand years of reactive porous flow.

Thus, the observed correlation between NiO and MnO in olivine (previous slide) rules out continuous, reactive porous flow of melt through the lower oceanic crust to form the upper crust. In other words, the chemical layering observed in the Oman ophiolite is not compatible with a process involving substantial fluxes of melt by porous flow through the gabbroic crustal section. Many workers have interpreted on-axis seismic data for lower crust beneath spreading ridges to indicate the presence of a high porosity “crystal mush”, with interconnected melt pores facilitating diffuse porous flow of melt through the crust to a shallow melt lens (e.g., Sinton & Detrick, JGR 1992) and “grain boundary sliding”at low viscosity during lower crustal ductile deformation in a gabbro glacier (e.g., Nicolas & Ildefonse, GRL 1996; Chenevez & Nicolas, GRL 1997). These ideas cannot apply to the Oman crustal section studied by Browning (and later by Korenaga & Kelemen). There was little if any diffuse porous flow of melt, or melt-lubricated grain boundary sliding in interconnected melt porosity after the formation of the chemical layering documented by Browning. Instead, melt transport through the lower crust must have been highly focused in cracks or - as yet unidentified - high porosity conduits.

Is there chemical layering like this in fast-spreading Pacific Ocean crust? If so, how are melts transported from the MTZ to the shallow melt lens, and to sheeted dikes and lavas in the upper crust? A full crustal section from the Pacific will be vital in addressing these first order dynamical questions.

Figure from Korenaga & Kelemen, EPSL 1998.



OK then, c or d?

One final point about chemical layering. The analysis of Korenaga & Kelemen, EPSL 1998, indicates that diffuse porous flow of melt through lower crustal gabbros did not occur in the Oman ophiolite after formation of the chemical layering. Melt-lubricated grain boundary sliding is an intrinsic part of the gabbro glacier hypothesis (there is no evidence for crystal plastic deformation in Oman ophiolite lower crust, so melt lubrication is required if there was a gabbro glacier at all). Because melt lubrication cannot have occurred – at least, not after formation of the chemical layering observed in Browning's data – this seems to indicate that there was no gabbro glacier - as in the sheeted sill hypothesis in panel d - or that the chemical layering formed by emplacement of sills "off axis", into a pre-existing gabbro glacier, as in the modified gabbro glacier model in panel c (e.g., Boudier et al., EPSL 1996).

Figure from Korenaga & Kelemen, EPSL 1998

if ~ half the rocks are “glacier” then at least half is sills

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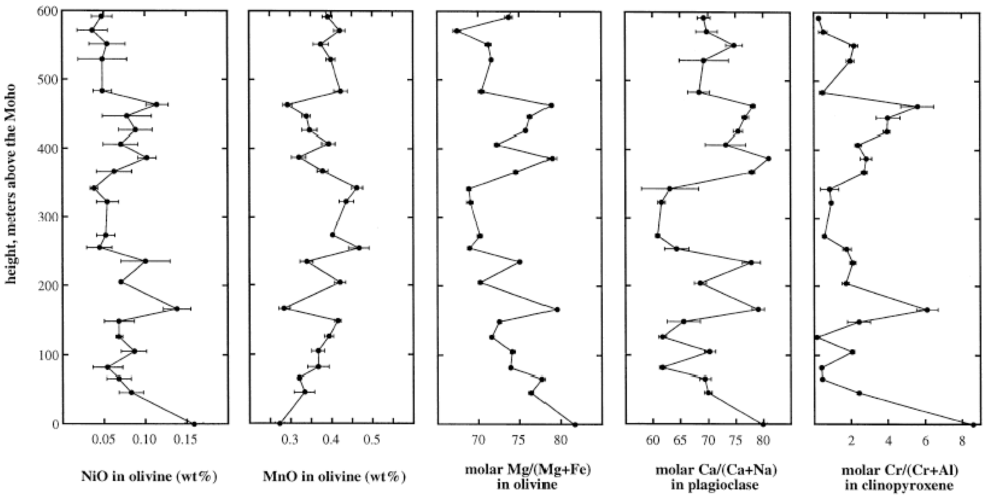
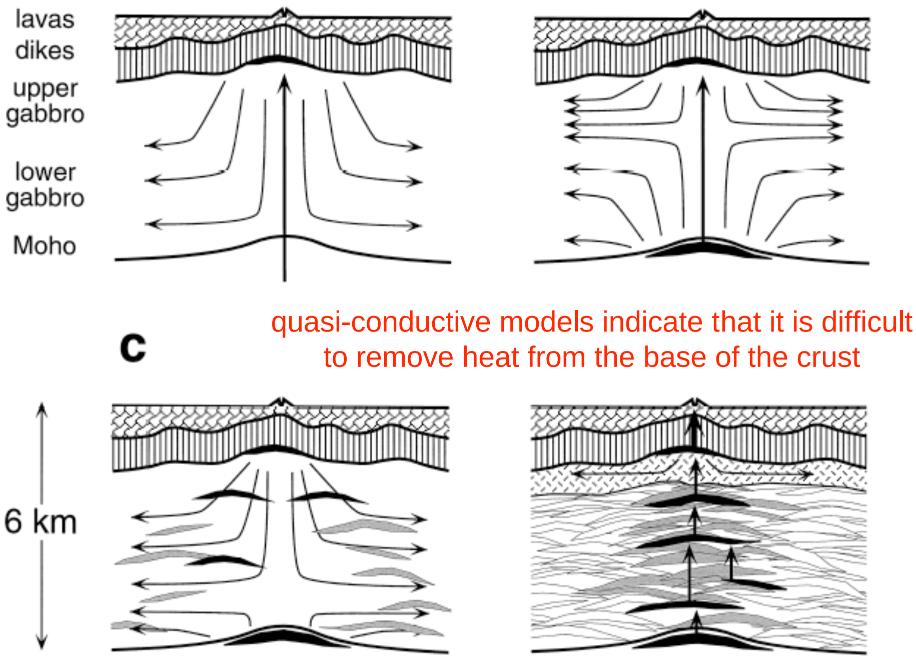


BUT WE DON’T KNOW SPREADING RATE FOR OMAN!!!

Well, OK, but since amost every data point is an inflection point in the chemical layering data for the Oman lower crust, if one set of rocks (let’s say the group with low Mg# in olivine) formed in a gabbro glacier, then the other set of rocks must have formed in sills, and this would be about half of the crustal section based on these data.

However … the data are very limited, due to the limitations of geological sampling with a hammer, and again, the chemical layering observed in the Oman ophiolite has an unknown relationship tochemical structure in fast spreading crust formed in the Pacific.

some thermal models favor gabbro glacier for fast spreading



quasi-conductive models indicate that it is difficult to remove heat from the base of the crust

Despite the geological and geochemical evidence from Oman, many workers - particularly geophysicists - tend to favor a gabbro glacier model for Pacific crust because some thermal models suggest that heat cannot be removed fast enough from the base of Pacific ocean crust to permit crystallization of substantial volumes of gabbro (e.g., Chen JGR 2001).

recent models explicitly include hydrothermal convection

sheeted sills
60 km/Myr

max cooling rate
in lower crust
~ 0.1°C/yr
~ 1 10^5 °C/Myr

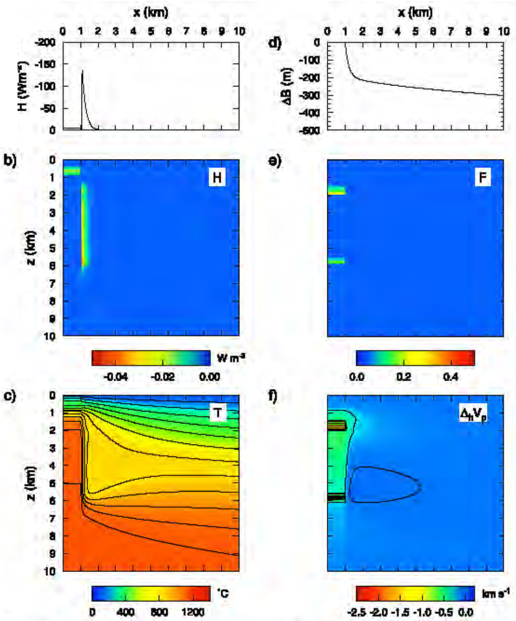


Figure 8. Many sills model using distribution of crystallization shown in Figure 5c and an axial intrusion region width of $A = 1000$ m. (a) Vertically integrated heat removal due to hydrothermal circulation with $\tilde{H} = 5.6$ W m^{-2}, $H_{\max} = 120$ W m^{-2}, $\lambda = 200$ m, $\Delta = 100$ m. (b) Distribution of hydrothermal heat removal, $H(x, z)$, throughout the crust. (c) Temperature structure. (d) Bathymetric variation predicted using isostatic model. (e) Calculated melt fraction within the crust. (f) Horizontal P wave velocity anomaly predicted from temperature and melt fraction. See text for details.

As pointed out by Cherkaoui et al., G-cubed 2003 and MacLennan et al., G-cubed 2004, the proportion of igneous rocks that can be crystallized at the base of fast spreading oceanic crust depends on the spatial distribution and vigor of lower crustal hydrothermal convection. Phipps Morgan & Chen JGR 1993 and Chen JGR 2001 used a quasi-conductive model, in which they attempted to account for hydrothermal cooling by using an enhanced thermal conductivity, 8 to 10 times larger than actual thermal conductivity. However, actual convection can have spatially varying rates of advective heat transport, converging in the high permeability limit on highly focused vertical upflow near the ridge axis, with closely spaced, near vertical isotherms around a narrow zone of igneous crystallization extending to the base of the crust. This figure, from MacLennan et al., shows such an end-member model. Accretion of the lower crust via a sheeted sill mechanism, combined with high lower crustal permeability during hydrothermal convection, yields lateral cooling rates ~ 1E5°C/yr via crustal flow across closely spaced, nearly vertical isotherms spanning the lower crust. In a natural system, cooling rates might be even higher, since the value of 1E5°C/yr may be a lower limit resulting from low model resolution in the region with tightly spaced isotherms.

gabbro glacier
60 km/Myr

max cooling rate
in lower crust
~ 0.02°C/yr
~ 2 10^4 °C/Myr

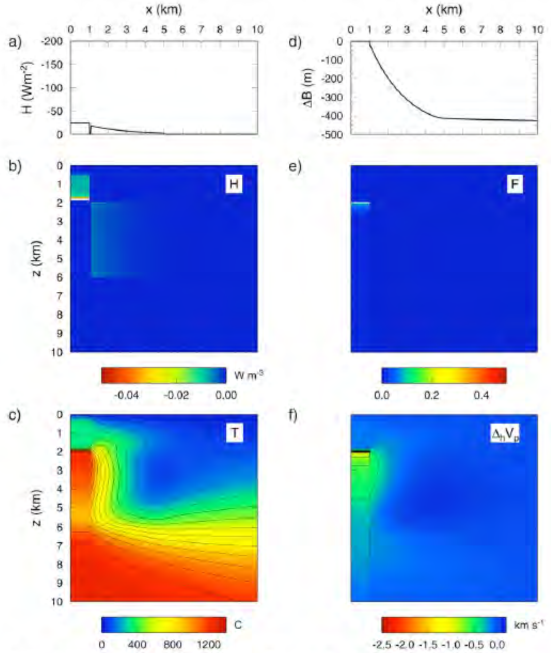
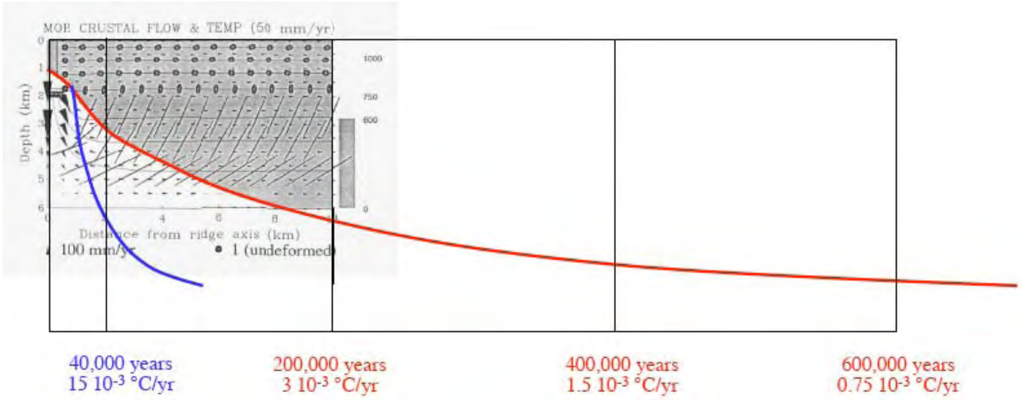


Figure 10. Gabbro glacier model using distribution of crystallization shown in Figure 5d and an axial intrusion region width of $A = 1000$ m. Vertically integrated heat removal due to hydrothermal circulation with $\bar{H} = 24.4$ W m^{-2}, $H_{max} = 18$ W m^{-2}, $\lambda = 2000$ m, $\Delta = 100$ m. Arrangement of plots as for Figure 8.

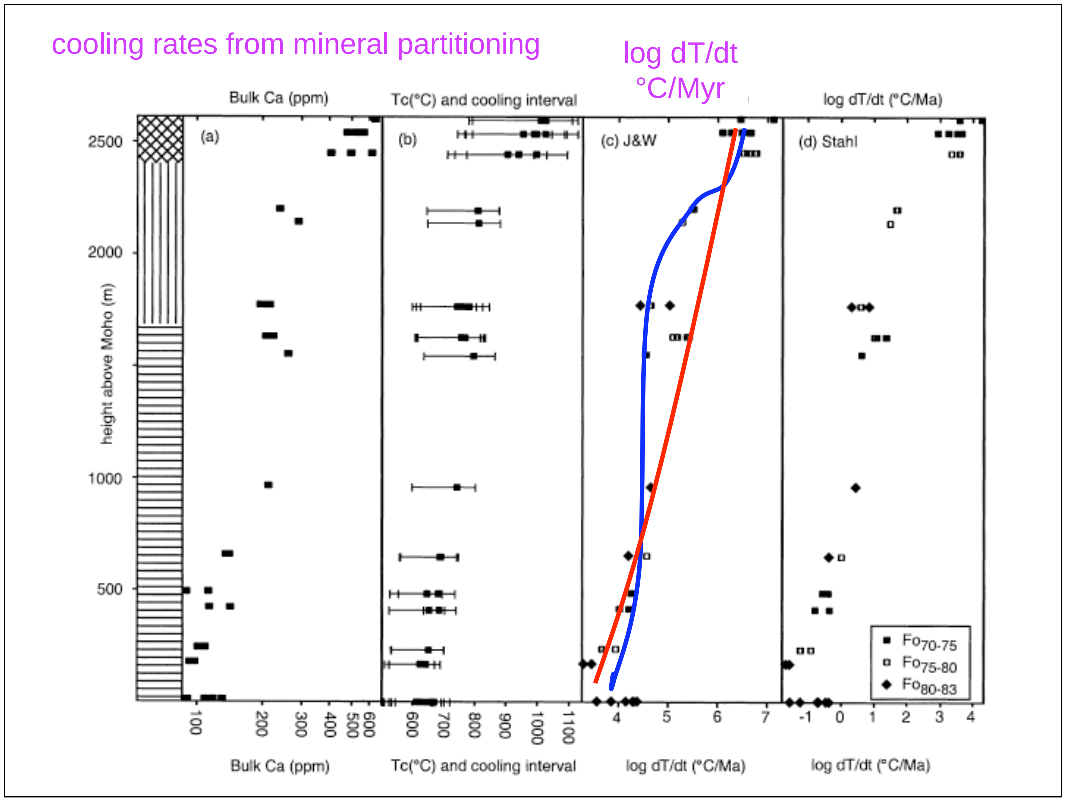
Here, MacLennan et al. illustrate results of a much more subdued lower crustal hydrothermal regime, generated via a gabbro glacier model, with relatively low lower crustal permeability. The predicted cooling rates are a factor of five smaller than in the model in the previous slide.

closure temperatures, cooling rates, and radiometric ages differ widely for different hydrothermal convection processes



Here, the red and blue lines show different cooling rates similar to those in the previous two slides, superimposed on model results from Phipps Morgan & Chen, JGR 1993. Very vigorous hydrothermal convection in the lower crust near the ridge axis would produce a cooling history and thermal structure similar to that in the blue curve, in which rocks at 6 km depth below the seafloor cool through ~ 600°C about 2 km off axis, after about 40,000 years, for a time integrated cooling rate of 15E-3°C/yr. In contrast, the red curve would result from hydrothermal cooling via diffuse convection, which can be modeled to a first approximation using an enhanced thermal conductivity as in Phipps Morgan & Chen, 1993. Here, rocks 6 km below the seafloor cool through 600°C about 10 km off axis, after about 200,000 years, with a cooling rate of 3E-3°C/year.

The closure temperature for the Ar/Ar radiometric dating technique using the mineral hornblende is ~ 600°C, as is the closure temperature for Sm-Nd and Lu-Hf radiometric dating techniques using mineral isochrons. Zircon in late, near-solidus melts that form oceanic tonalites and trondhjemites forms at 800 to 600°C. High precision radiometric dating of 10 to 15 Myr samples from undisturbed oceanic lower crust, sampled via drilling, should reveal a pattern of younger ages with greater depth, and the change in age versus depth should permit us to distinguish between models represented by the blue versus red curves.

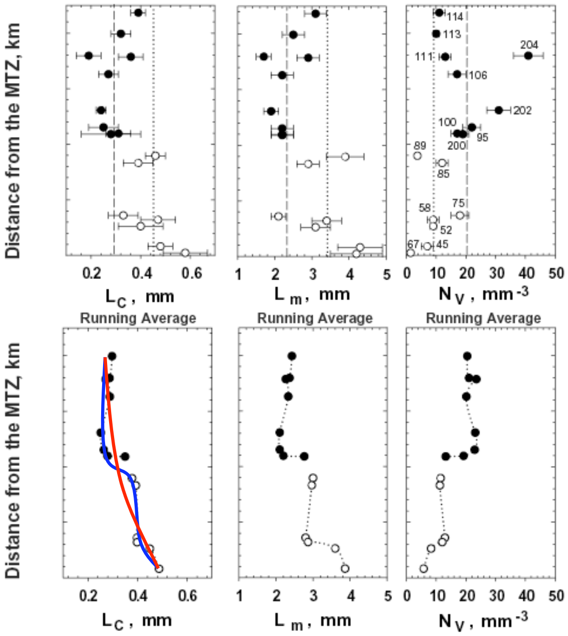


In addition, mineral compositions can be used to estimate cooling rates. For example, this illustration from Coogan et al., EPSL 2002 uses data on the concentration of Calcium (Ca) in olivine to estimate “closure temperatures” for Ca-Mg exchange between olivine and clinopyroxene, and hence - together with experimental data on Ca diffusion in olivine - to estimate cooling rates as a function of depth in a lower crustal section from the Oman ophiolite. Because experimental data on Ca diffusion in olivine available in 2002 were not consistent between labs, Coogan et al. showed two sets of estimated cooling rates. We now know that the data of Jurewicz & Watson (J&W, panel c) are more consistent with recent measurements (Coogan et al. GCA 2005). Given continuing uncertainty about diffusivities, however, the pattern of cooling rate versus depth is more important than the quantitative estimates of cooling rate for particular samples.

The red curve is Coogan’s interpretation of his data, with a constant gradient in cooling rate, resembling predictions from gabbro glacier models. The blue curve is an alternative interpretation (e.g., Garrido et al., G-cubed 2001), with a constant cooling rate over a long interval in the oceanic lower crust arising from crustal spreading through near-vertical isotherms.

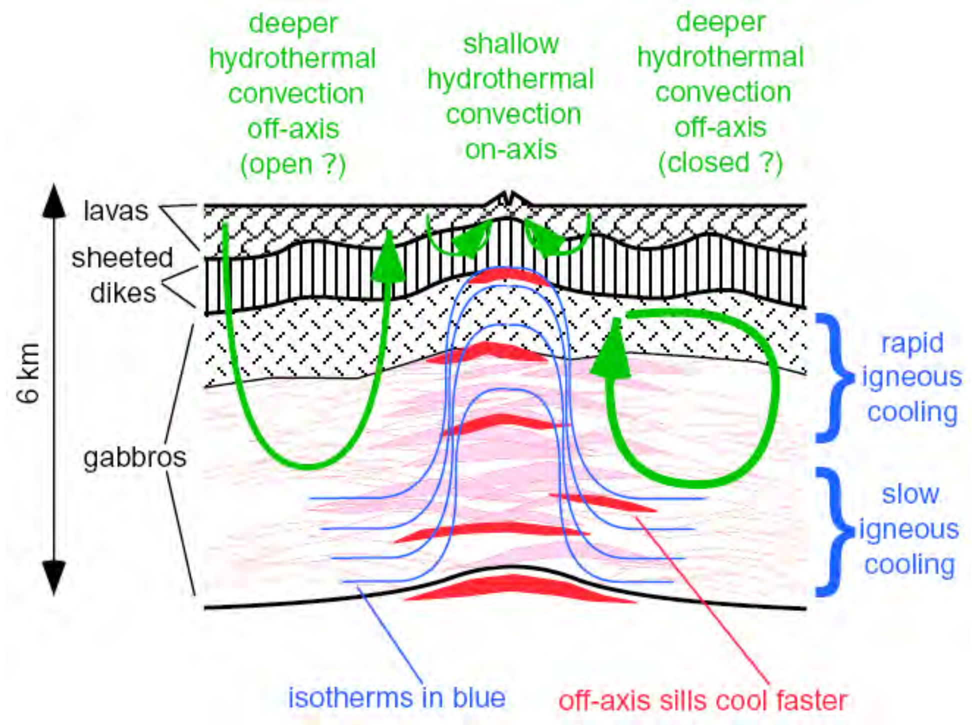
The different interpretations of the data are possible because of the limited number of samples, and the incomplete characterization of the nature and reasons for small scale variability between different olivine grains and between closely spaced samples. In addition, of course, the relevance of these data to processes beneath a fast-spreading ridge is uncertain, due to the unknown spreading rate (and tectonic provenance) of the Oman ophiolite. A more complete data set from a full crustal hole through Pacific oceanic crust would address all of these problems.

cooling rates from crystal size statistics

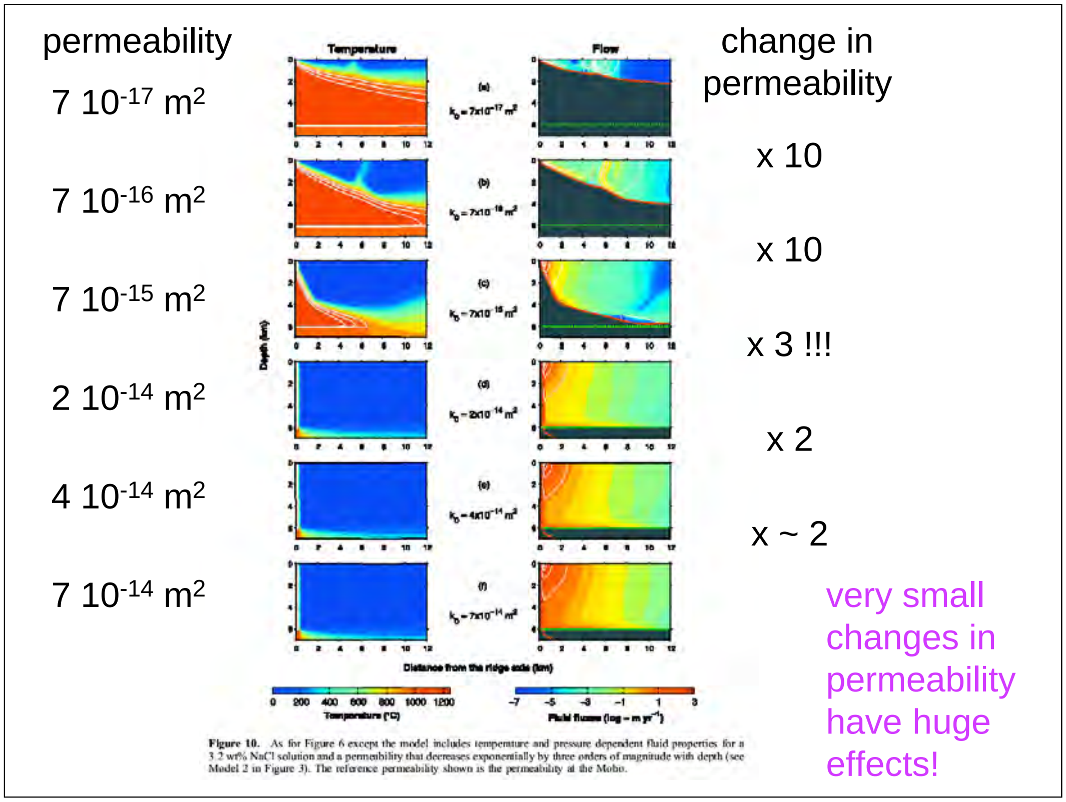


Cooling rates for igneous and metamorphic rocks can also be estimated from crystal size distributions (see, e.g., work by Marsh, Cashman, and their co-workers). Here is a data set on crystal size distributions (characteristic size, Lc, maximum size, Lm, and crystals per unit volume, Nv) from Garrido et al., G-cubed 2001. In general, Lc and Lm are smaller, and Nv is larger, for higher cooling rates. Garrido et al. interpreted the data to indicate a bimodal distribution of cooling rates (blue curve), resulting from active hydrothermal convection extending halfway down into the gabbro section from the seafloor. Probably, however, Coogan et al. (EPSL 2002) would interpret these data differently, with a continuous decrease in cooling rates with increasing depth below the seafloor (red curve). A data set with higher resolution will be required to determine which interpretation is best.

This type of study would be best done by a group of scientists concentrating their efforts on a single core, and of course would be more useful for the Pacific where the spreading rate and tectonic setting are well known.



Interpretation from Garrido et al. (G-cubed 2001) explaining bimodal cooling rates for oceanic lower crust, inferred from crystal size data in the Oman ophiolite, as a result of vigorous hydothermal convection through the upper half of the gabbro section.



permeability

7 10^{-17} m^2

7 10^{-16} m^2

7 10^{-15} m^2

2 10^{-14} m^2

4 10^{-14} m^2

7 10^{-14} m^2

change in permeability

x 10

x 10

x 3 !!!

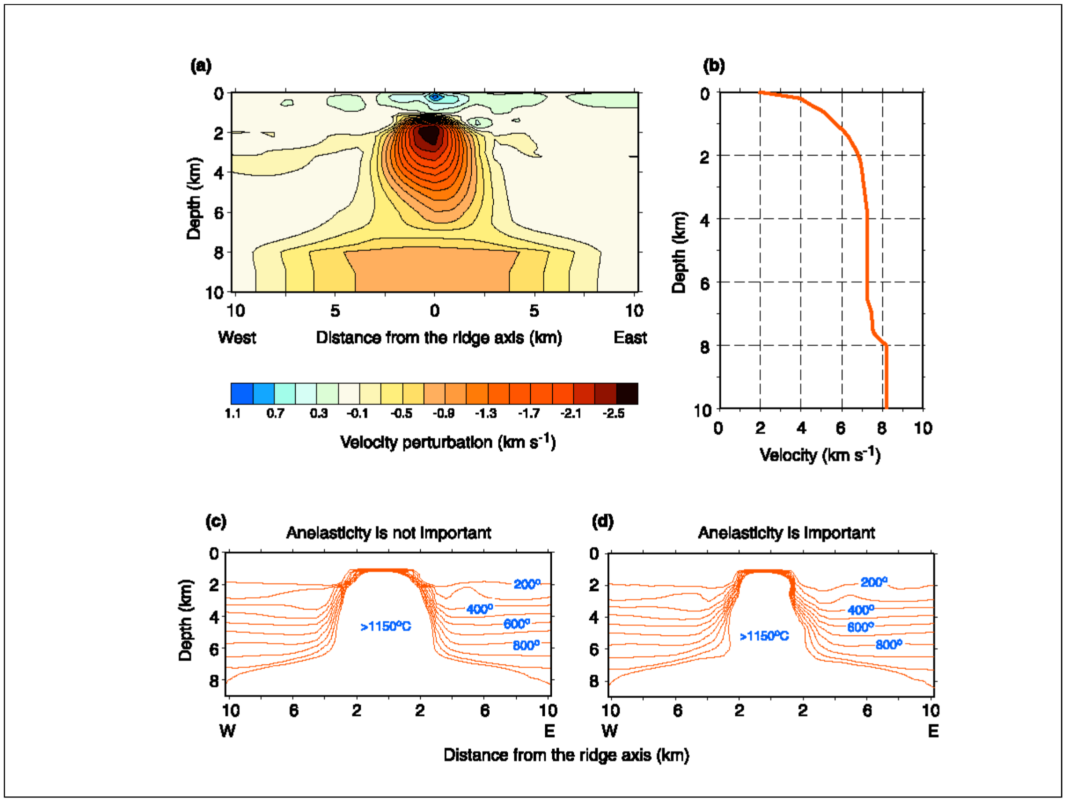
x 2

x ~ 2

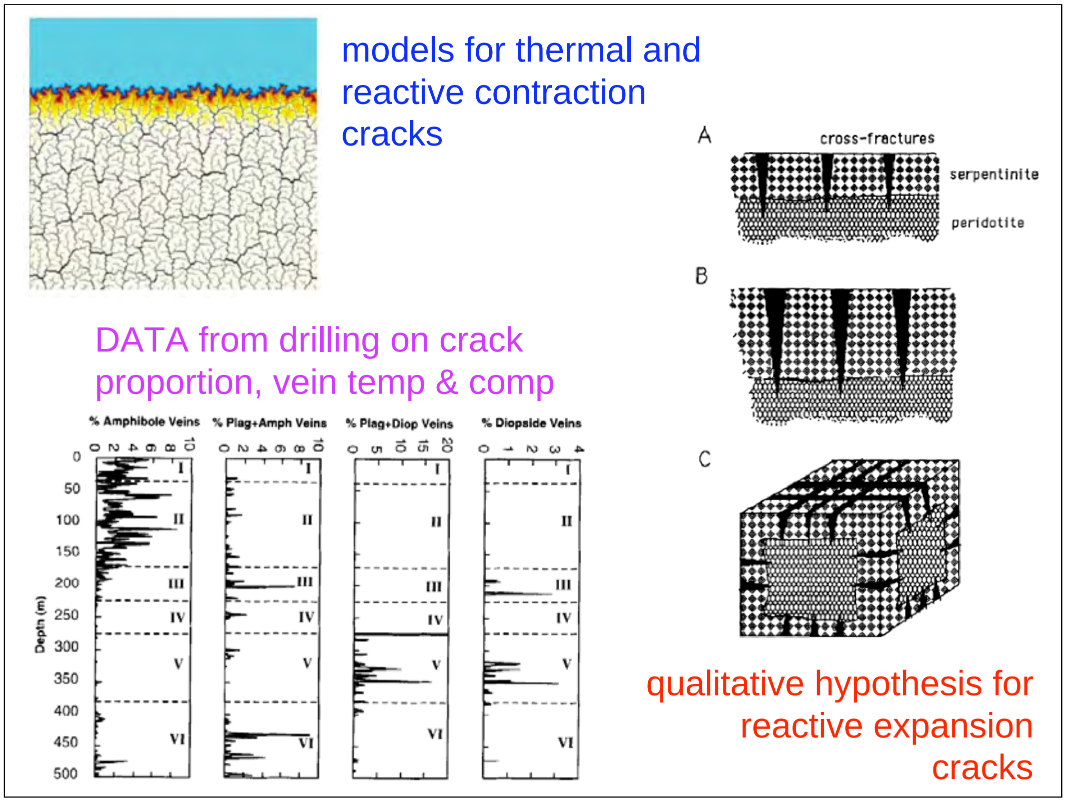
very small changes in permeability have huge effects!

Figure 10. As for Figure 6 except the model includes temperature and pressure dependent fluid properties for a 3.2 wt% NaCl solution and a permeability that decreases exponentially by three orders of magnitude with depth (see Model 2 in Figure 3). The reference permeability shown is the permeability at the Moho.

The modeling study of Cherkaoui et al., G-cubed 2003, focused on the effect of lower crustal permeability on hydrothermal convection. They found that, at a critical value, the pattern of hydrothermal convection changed radically with a very small change of permeability. Since the values of permeability both above and below this critical value are within the range of (very imprecise) estimates of large scale permeability in oceanic lower curst, it is doubtful whether continued crustal scale modeling, or additional hydrological measurements alone, will resolve whether fast-spreading crust cools via an “enhanced conductivity” as in the upper panels, or via highly focused, near-ridge advection, as in the lower panels.



These data on crustal seismic structure from the East Pacific Rise (Dunn et al JGR 2002) – together with their interpretation in terms of temperature – were used to infer that lower crustal permeability is high, and vigorous hydrothermal convection extends to the base of the crust. However, the data processing and interpretation remain open to question.



models for thermal and reactive contraction cracks

DATA from drilling on crack proportion, vein temp & comp

qualitative hypothesis for reactive expansion cracks

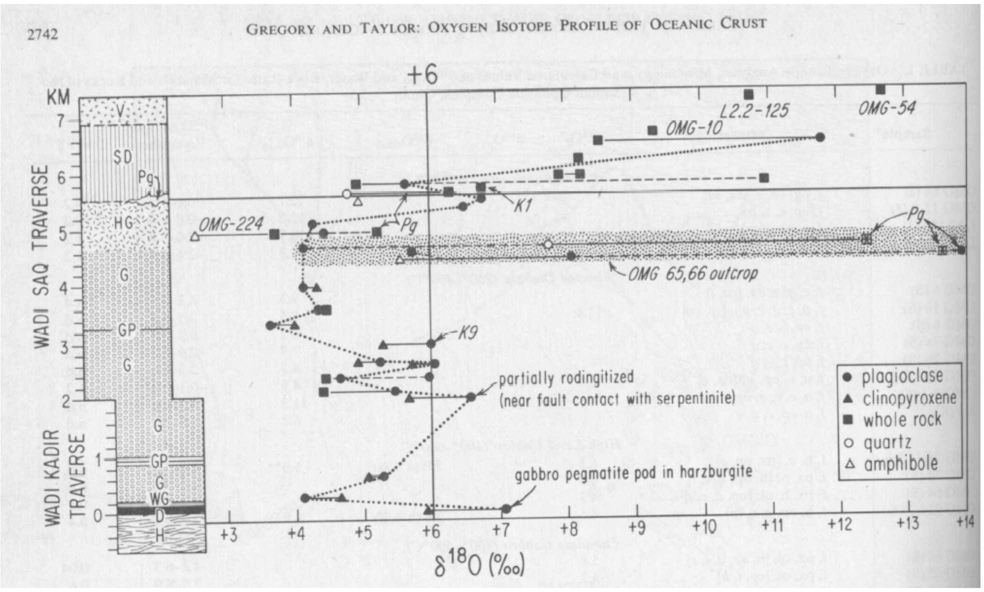
Instead, observational data on crack and vein distribution need to be combined with small scale physical models of thermally and chemically driven cracking. Modeling has begun, but there are very few serious studies of vein size/frequency distributions, and no crustal scale census of such veins. Large scale, non-linear dependence of permeability on temperature and cooling rate can be characterized using small scale models, tested against field data on crack distribution as a function of depth in the lower crust and uppermost mantle. Once the non-linear behavior is understood, it can be incorporated into large scale crustal models.

Figures in this slide from:

Mathe-Sorenssen et al. PRL 2006 for cracking driven by reactive dissolution and contraction of minerals in fluid migrating along cracks, upper left;

O'Hanley Geology 1992, for cracking driven by hydration and expansion of minerals via reaction with fluid migrating along cracks, right;

Magde et al. EPSL 1996 on metamorphic vein distribution in oceanic lower crustal gabbros from ODP Hole 735B along the SW Indian Ocean Ridge, lower left.



water/rock ratios from isotope geochemistry

This is a figure from the classic paper by Bob Gregory and Hugh Taylor (JGR 1981) on the variation of oxygen (and strontium) isotope ratios in the lower crustal gabbros of the Oman ophiolite. The x-axis in this diagram, delta^{18}O in parts per thousand, or "per mil", is the difference between ^{18}O/^{16}O in a sample and ^{18}O/^{16}O in "standard mean ocean water" (SMOW), normalized by the ^{18}O/^{16}O ratio in SMOW. Relative to a mantle value of delta 18O of about 6 per mil, Gregory and Taylor documented shifts toward heavier ^{18}O/^{16}O in shallow volcanics and sheeted dikes, and lighter ^{18}O/^{16}O in lower crustal gabbros. Shallow, low temperature alteration shifts minerals and rocks to heavier ^{18}O/^{16}O, because the lighter isotope of oxygen, ^{16}O is significantly more volatile than the heavier ^{18}O, and so ^{16}O is preferentially partitioned into fluid, leaving a heavier solid residue. At high temperature, there is little energetic difference between ^{18}O and ^{16}O; the lower delta ^{18}O values for lower crustal gabbros simply reflect mixing between sea water oxygen (delta ^{18}O = 0) and oxygen in mantle derived igneous rocks. From these data, Gregory and Taylor inferred a relatively small water/rock ratio, indicating a relatively small time-integrated flux of seawater through the Oman lower crust. However, note that Gregory and Taylor tried to sample typical or "average" lower crustal gabbros, and avoided highly altered rocks.

multiple scales of hydrothermal circulation & alteration

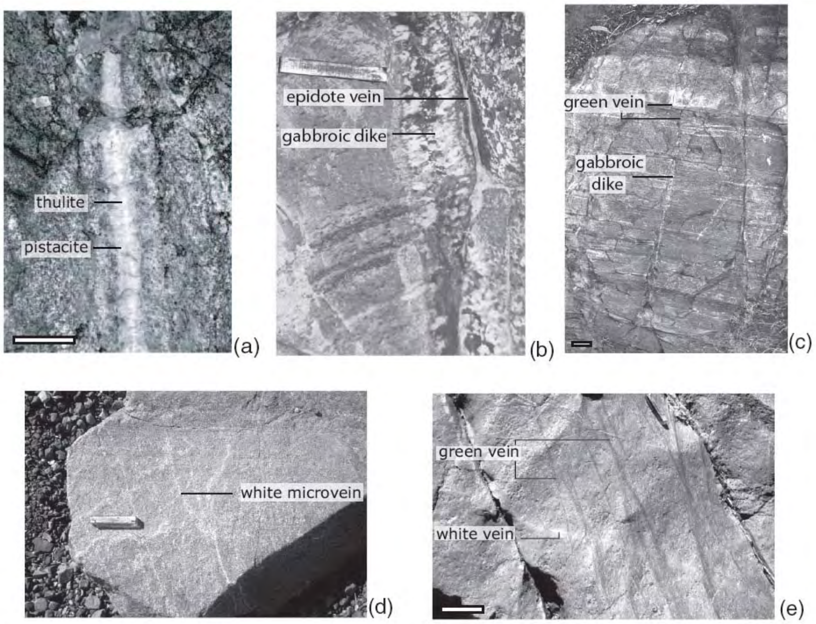
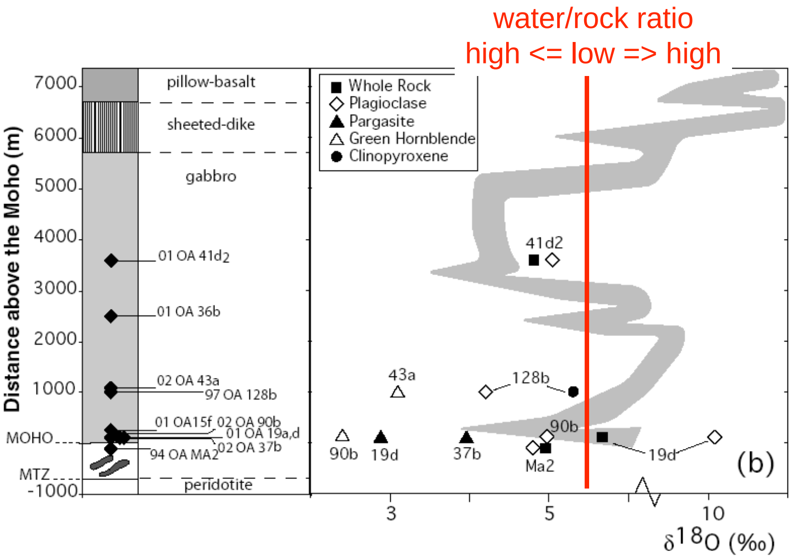


Fig. 6. Field relationships of dykes and veins (scale bar represents 10 cm). (a) Thulite–pistacite vein cross-cutting a foliated gabbro matrix. Reaction margins marked by the development of secondary clinopyroxene (01 OA36b). (b) Comb-like structure in gabbroic dyke. A pink epidote vein follows the margin of the dyke (01 OA15f). (c) Along-strike transition from a gabbroic dykelet to a hydrothermal green amphibole vein. (d) White prehnite vein. (e) Green amphibole vein cross-cut by white prehnite vein.

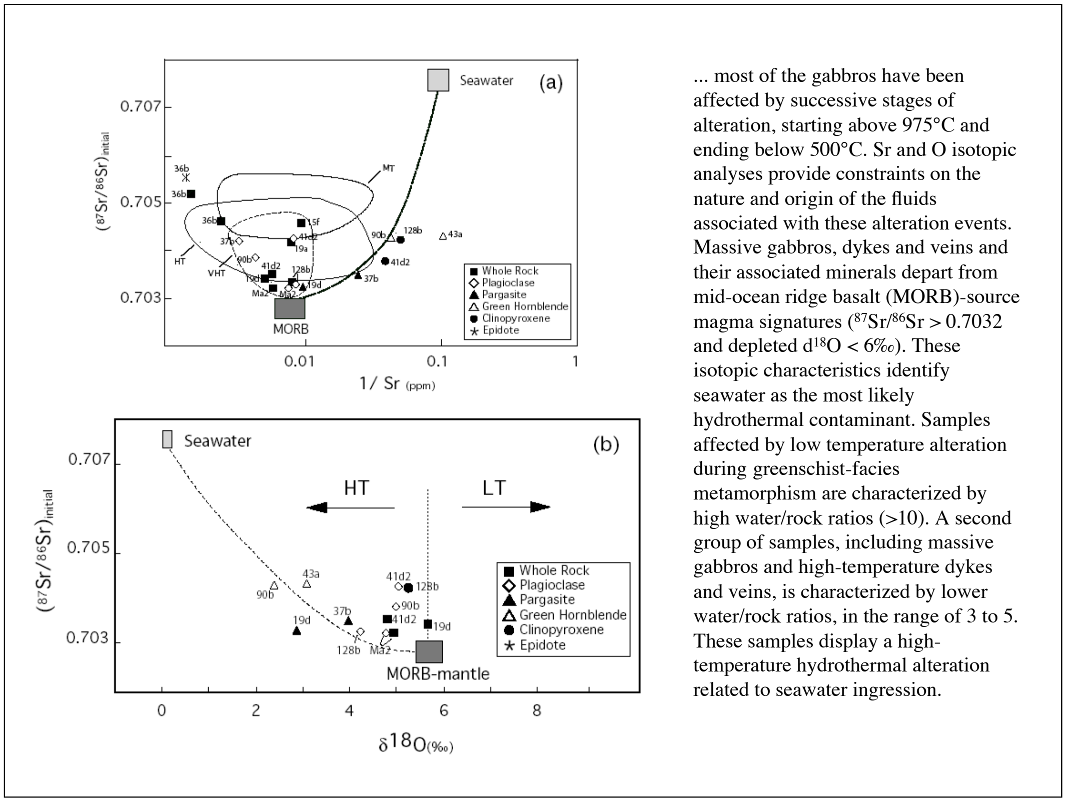
This figure, from a paper by Bosch et al. in J. Petrol. 2004, shows a variety of hydrothermal alteration veins, with a 10 cm scale bar in each photo. Gregory & Taylor avoided sampling such veins. Bosch et al, made a study similar to that of Gregory & Taylor, but focusing on these veins.

oxygen data yield much higher water/rock ratios when high temperature veins are incorporated



but what are the relative proportions?
DRILL (and ANALYZE)

In this figure, Bosch et al. contrasted their results for hydrothermal veins with the earlier data on less altered gabbroic rocks from Gregory & Taylor (grey band). The vein assemblages show much larger shifts in delta ^{18}O from igneous values toward seawater, clearly recording much higher water/rock ratios. However, this does not allow us to determine the kilometer-scale permeability, of the lower crust, or the overall role of hydrothermal convection in cooling the Oman lower crust. This is so because there is no accurate measurement of the abundance of veins in the Oman lower crustal section. In fact, because altered rocks tend to weather more easily than fresh gabbros in Oman, even a hands-and-knees census of vein abundance in outcrop would not yield a reliable value. Only drill core with relatively high recovery could reveal the overall proportion of hydrothermal veins, and thus the large scale permeability, water/rock ratio, and hydrothermal cooling processes for the Oman section. Similar data from Pacific Ocean crust would be even more valuable.

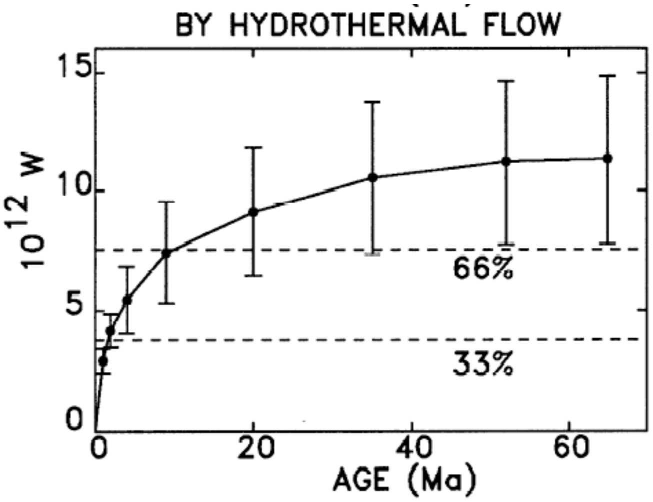


... most of the gabbros have been affected by successive stages of alteration, starting above 975°C and ending below 500°C. Sr and O isotopic analyses provide constraints on the nature and origin of the fluids associated with these alteration events. Massive gabbros, dykes and veins and their associated minerals depart from mid-ocean ridge basalt (MORB)-source magma signatures ($^{87}Sr/^{86}Sr > 0.7032$ and depleted $d^{18}O < 6‰$). These isotopic characteristics identify seawater as the most likely hydrothermal contaminant. Samples affected by low temperature alteration during greenschist-facies metamorphism are characterized by high water/rock ratios (>10). A second group of samples, including massive gabbros and high-temperature dykes and veins, is characterized by lower water/rock ratios, in the range of 3 to 5. These samples display a high-temperature hydrothermal alteration related to seawater ingression.

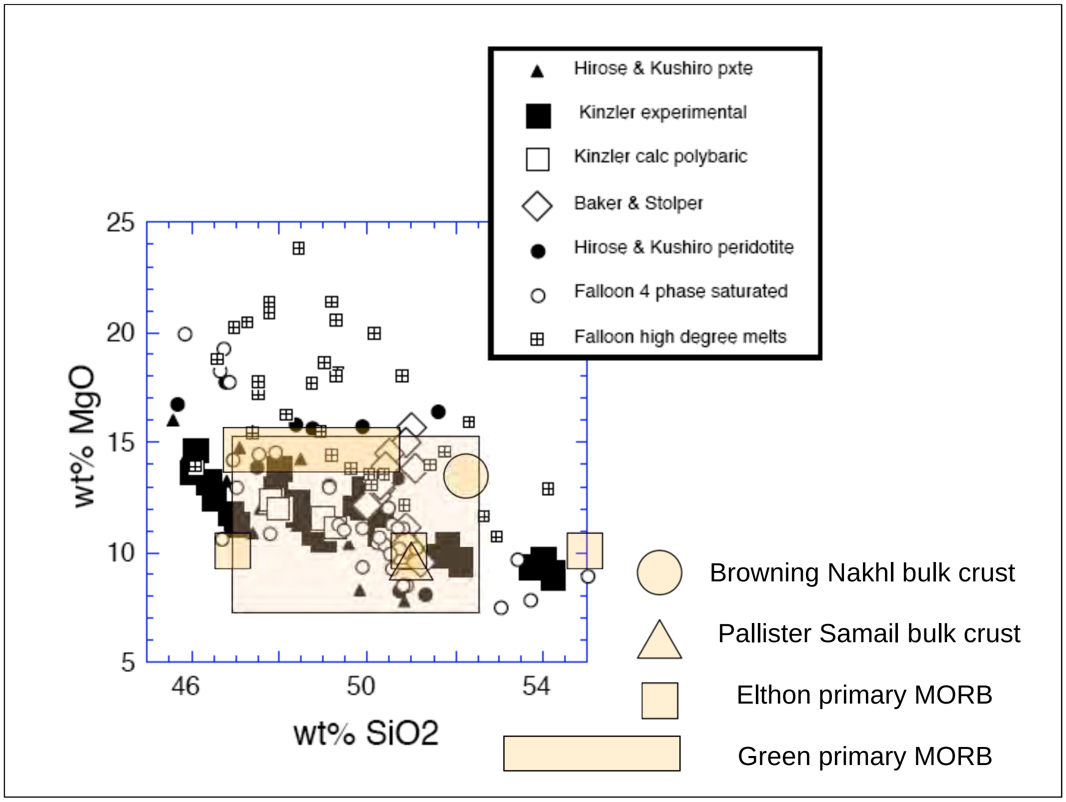
Figures and discussion of water/rock ratio from Bosch et al J Petrol 2004. Unlike Gregory & Taylor (JGR 1981), who inferred water/rock ratios ~ 1 from their oxygen and strontium isotope data on relatively fresh gabbros, Bosch et al. infer water rock ratios from 3 to 10 for alteration veins. Note that such chemically based water rock ratios are minima, since they do not account for recirculation of water that is already equilibrated with lower crustal rocks, nor do they account for transport of fluids that are out of chemical equilibrium with surrounding rocks. Since heat diffuses much faster than chemical species, the thermal water/rock ratio is greater than or equal to the chemical water/rock ratio.

The importance of circulation in veins on the overall cooling of oceanic lower crust depends on the style of circulation (closed or open), kinetic factors, and the (unknown) total proportion of veins in oceanic lower crust. Direct measurements of vein proportion in drill core will address this first order problem, as will chemical analyses of veins and host rocks, and measurements of lower crustal cooling rate described earlier in this presentation.

heat flow data indicate that hydrothermal cooling extends to > 10 Ma crust



Up to this point, we have focused on near-axis, high temperature fluid convection in lower oceanic crust. This figure from Stein & Stein (JGR 1994) illustrates the inferred heat extracted from the oceanic crust via focused hydrothermal advection (rather than diffuse, "conductive" heat flow). Substantial, ongoing, low temperature advective heat transport is inferred for 10 to 15 Myr old crust, suggesting that drilling this age lower crust may yield direct samples of the advective fluid flow networks responsible for off-axis hydrothermal convection.



Shifting gears, it should be emphasized that many first order results can be obtained simply from the composition of oceanic lower crust. The simplest issue is that the bulk composition of oceanic crust is unknown at present; the volcanic and dike sections are reasonably well characterized, but the bulk lower crustal composition is comparatively unknown. This may be surprising to some people, but the average primitive magma composition that is extracted from the mantle to form mid-ocean ridge basalts (MORBs) and complementary gabbros is not well known, and is essentially model dependent. This problem arises because the mantle potential temperature beneath the ridges is not well known, nor are "shape" of the melting region and the overall process of melt extraction well characterized. The average melt fraction, the maximum, minimum and average degree of melting, the mode of melt transport (equilibrium porous flow versus chemically isolated, focused flow), and the shape of the region of melt extraction (triangular, columnar in 2D, or cylindrical) are still topics of active debate.

The figure here – based on a compilation of experimental and estimated mantle melt compositions at 5 to 30 kb by Kelemen & Holbrook (JGR 1995) – gives a general idea of the level of uncertainty. The more silica-rich peridotite melts, with SiO2 > 52 wt%, formed by partial melting at less than 8 kb, can be ruled out, because primitive MORB has < 52 wt% SiO2 as you will see in a subsequent slide. Similarly, peridotite melts with more than ~ 15 wt% MgO are not likely precursors for MORB because they would require very high initial pressures of melting, and very high degrees of melting, inconsistent with estimates for the mantle temperature. This leaves the shaded region as a reasonable estimate for the current uncertainty regarding the average composition of mantle-derived melt extracted to form the oceanic crust.

If, at fast spreading ridges, most igneous crystallization and other differentiation processes take place in the crust rather than in the upper mantle, then the average composition of the entire crustal column should correspond to the average composition of melt extracted from the mantle. This would directly yield data much in demand for geochemists working on global scale chemical cycles, and in addition would shed valuable light on mantle potential temperature and the many other unknown factors listed in this paragraph. Such an approach was adopted in early ophiolite research, but increasing recognition of tectonic and compositional differences between ophiolites and "normal" Pacific Ocean crust rendered global application of the ophiolite results problematic.

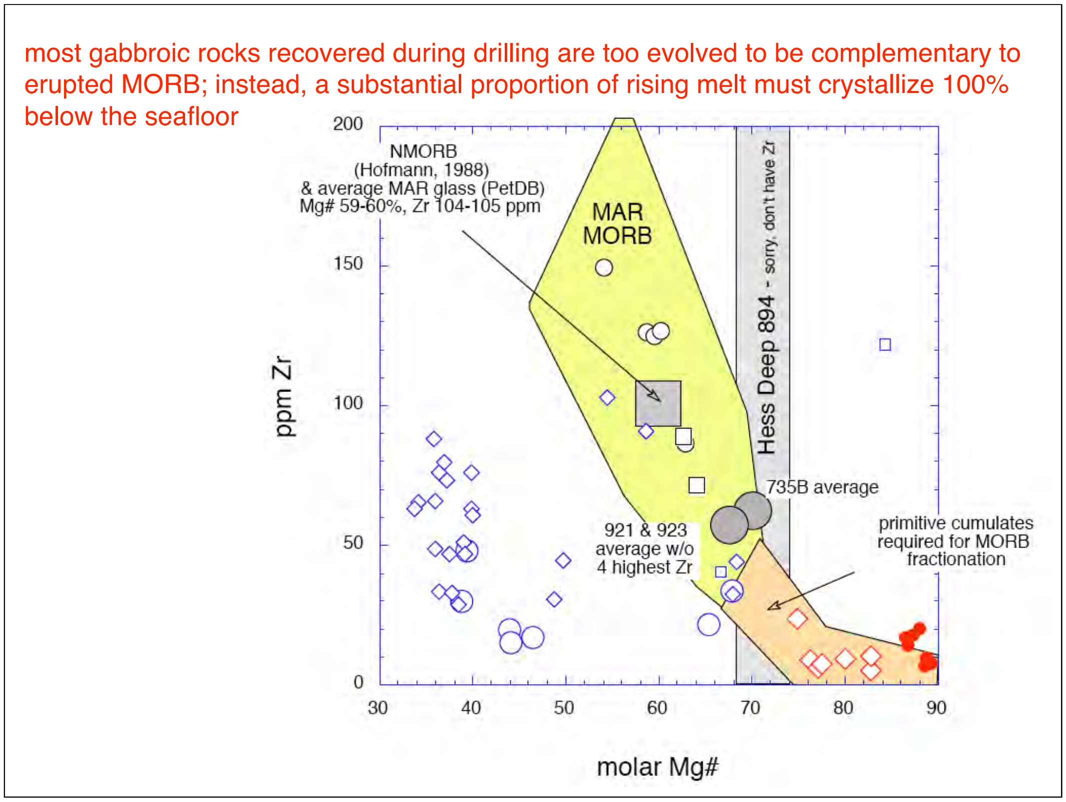
Additional data:

Browning Nakhl bulk crust: estimated bulk composition, Nakhl massif, Oman ophiolite, Browning thesis, Open University, 1982

Pallister Oman bulk crust: estimated bulk composition, Samail massif, Oman ophiolite, Pallister thesis, UC Santa Barbara, all published in Pallister & Hopson, Pallister & Knight, Pallister, all in JGR 1981

Elthon primary MORB: three end-members from Elthon et al., JGR 1992

Green primary MORB: Green et al., Eur J Mineral 2000



most gabbroic rocks recovered during drilling are too evolved to be complementary to erupted MORB; instead, a substantial proportion of rising melt must crystallize 100% below the seafloor

Another first order issue is to identify the nature and position of primitive cumulate plutonic rocks complementary to MORB. Cumulate plutonic rocks, in this context, are rocks formed by partial crystallization of a melt, after which the remaining melt was removed.

This diagram, relating molar Mg/(Mg+Fe), or Mg#, to ppm Zirconium in volcanic and plutonic rock samples, illustrates the problem. The large grey square encompasses the canonical MORB composition of Hofmann (EPSL 1988) and the average of Mid-Atlantic Ridge (MAR) MORB glasses from PetDB, both of which have ~ 100 ppm Zr. The yellow field encompasses the full range of MAR glasses, including primitive glasses with Mg# around 70% (in equilibrium with mantle olivine) and ~ 50 ppm Zr. If Zr were a perfectly incompatible element, the factor of two increase in Zr concentration from primitive to average MORB would require 50% crystal fractionation. Because finite amounts of Zr are incorporated into the solid products of crystal fractionation, the increase in Zr requires more than 50% crystallization, on average. Thus, lavas and sheeted dikes must be complemented by an equal mass of primitive cumulates, beginning with cumulates having an Mg# of about 90%, equivalent to that in the mantle residues of MORB formation.

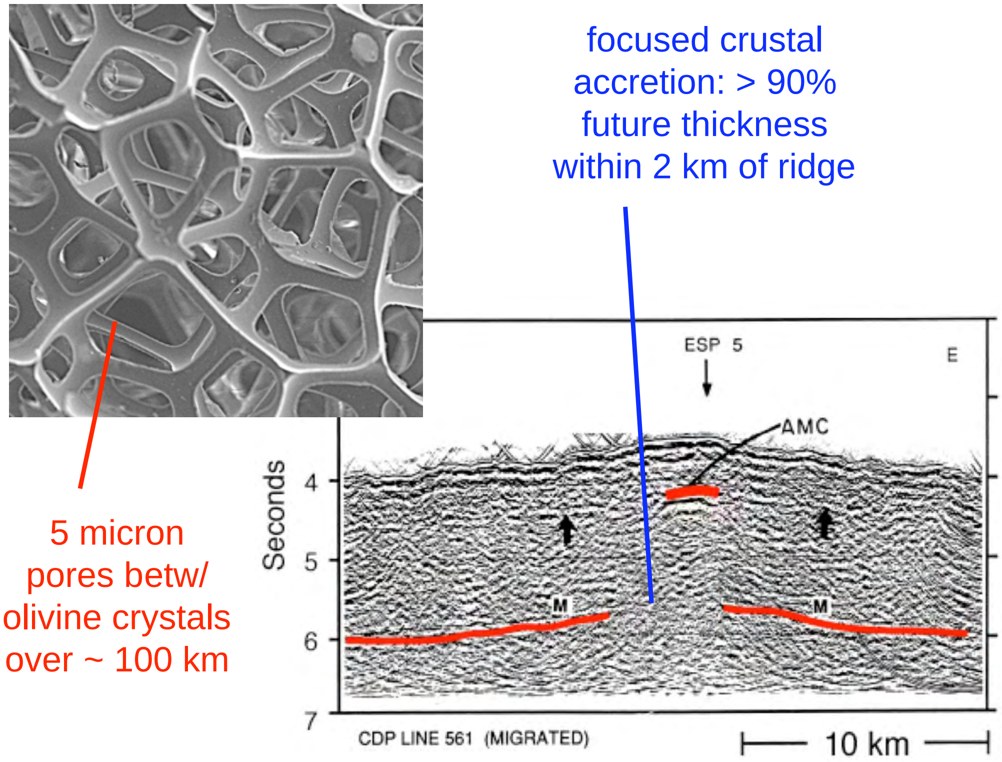
The required volumes of primitive cumulates have never been sampled in the oceans, though they are common in Oman ophiolite lower crust. The large grey circles on this diagram illustrate the average compositions of gabbroic rocks recovered by drilling from ODP Hole 735B on the SW Indian Ridge, and from Sites 921 and 923 in the MARK area on the Mid-Atlantic Ridge. Strikingly, these average compositions overlap the Mg# and Zr concentrations in primitive mid-ocean ridge basalts. Although Sites 735, 921 and 923 do contain some primitive gabbros, they also contain highly evolved "ferro-gabbros" and granitic veins. As a result, in bulk the samples recovered from these sites have liquid compositions. They cannot represent the primitive cumulates complementary to MORB fractionation. Similarly, gabbroic rocks sampled at ODP Site 894 in Hess Deep, from crust formed at the East Pacific Rise, have Mg# similar to primitive MORB, and cannot represent the required primitive cumulates complementary to average MORB.

The smaller symbols on this plot are plutonic rocks recovered during ODP Leg 209, from 14 to 16°N along the Mid-Atlantic Ridge. The red symbols are either "impregnated peridotites", formed by crystallization of melt in pore space within residual mantle peridotites, or hydrothermally altered samples from Site 1268 which may or may not preserve their igneous compositions. The blue symbols include gabbros drilled at all other sites, including 209 meters of gabbro in Hole 1275D. None of these rocks could be complementary to the crystal fractionation sequence seen in MORB from the 14 to 16°N region.

Where are the primitive cumulates at mid-ocean ridges? We know they must exist. In the Atlantic, they could be crystallized as plutons and impregnations emplaced within residual peridotites in the shallow mantle. However, how about in the Pacific? . In Oman, primitive cumulates are abundant in the lower crust. If Pacific crust is similar to Oman, then Site 894 gabbros from Hess Deep would correspond to the shallowest gabbros in Oman, and primitive cumulates form the bulk of the lower crust. True, or not?

Figure from Kelemen et al., ODP Leg 209 Initial Reports,

http://www-odp.tamu.edu/publications/209_IR/209ir.htm



focused crustal
accretion: > 90%
future thickness
within 2 km of ridge

5 micron
pores betw/
olivine crystals
over ~ 100 km

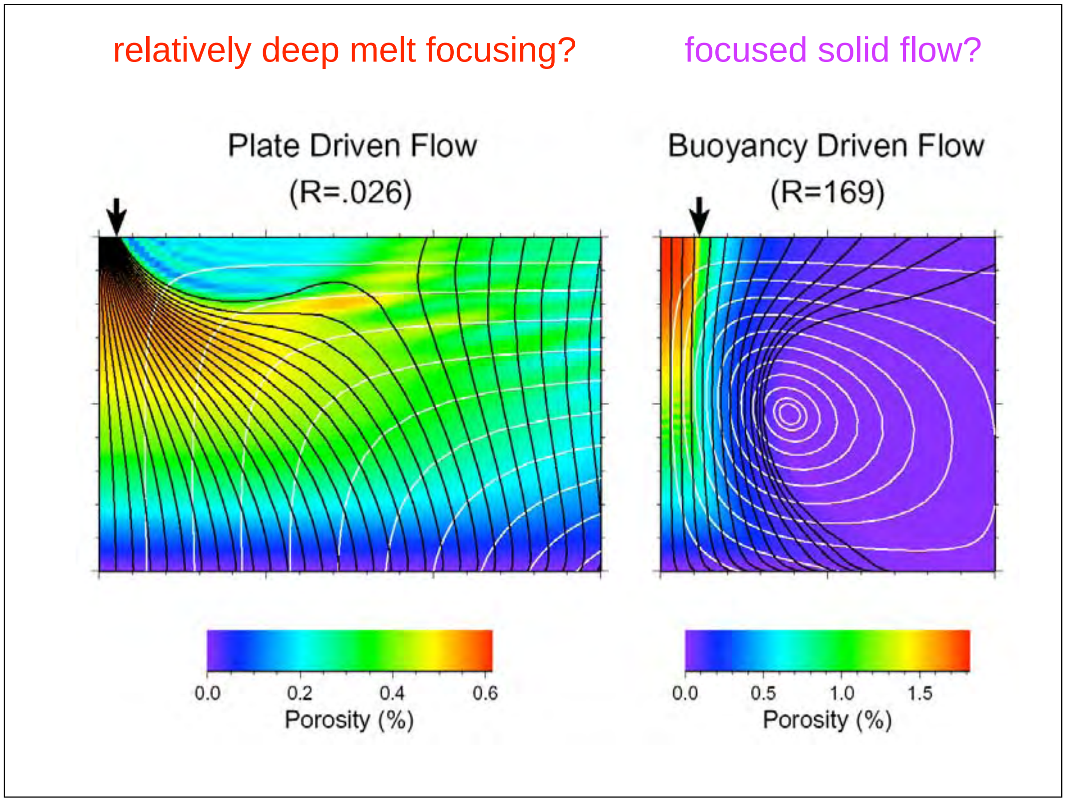
Finally, drilling can help constrain hypotheses on the miraculous focusing of melt extraction from the mantle at mid-ocean ridges. Melt in the mantle forms on micron scale pores along olivine crystal edges, over a region hundreds of kilometers wide. The upper left diagram is an SEM photograph of reticulite, glass veins that form along the edges of gas bubbles in lava. This structure is essentially identical to the structure of melt veins that form along the edges of olivine crystals in the mantle, with a vein width of a few microns.

Miraculously, much or all of that melt is extracted and crystallizes to form oceanic crust in a region less than 4 km wide along the East Pacific Rise. The figure on the lower right is a seismic reflection image of the crust in a section perpendicular to the EPR at 9°N. Since Moho is observed within a few km of the ridge axis, and the crustal thickness does not increase off axis, it is safe to assume that more than 90% of the igneous crust forms in the narrow ridge axis region. The new data of Singh et al. (Nature 2006) provide even less room for the crustal formation process, showing an essentially continuous Moho extending across the ridge axis.

How is melt flow focused from tiny pores over 100’s of km to 100% igneous rock in a crustal accretion region a few km wide? As for the mechanism of crustal formation (gabbro glaciers versus sheeted sills), there are well defined hypotheses that have been clearly outlined, but no clear consensus on the answer.

The next few slides outline the various hypotheses on melt focusing mechanisms, and then address how data from a drill hole penetrating the upper few km of the mantle beneath fast-spreading crust could help to distinguish between the hypotheses.

Upper left figure from Wark et al., JGR 2003. Lower right figure from Vera et al., JGR 1990.



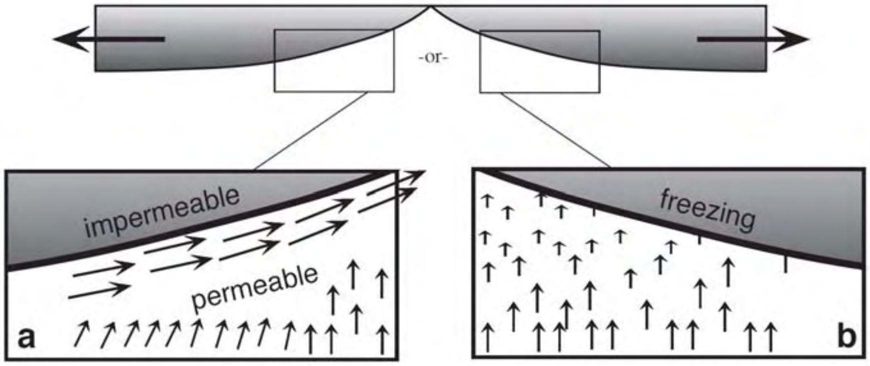
relatively deep melt focusing? focused solid flow?

Two proposed mechanisms for focused crustal accretion are illustrated above, in a figure based on calculations by Spiegelman EPSL 1996. In looking at these, please keep in mind that melt forms in the mantle beneath spreading ridges primarily as a result of adiabatic decompression. Solid peridotite at depth passes upward through its solidus – here, at the bottom of the diagrams – and gives rise to partial melts as it moves toward the surface.

The lefthand diagram illustrates the hypothesis that melt flow is focused by a kind of suction toward the spreading ridge, while solid flow in the mantle is via plate driven, "passive upwelling". Because the plates pull apart, one can envision that there is a region of low pressure just beneath the spreading ridge, and that melt is pulled into this region (Spiegelman & McKenzie, EPSL 1997; Phipps Morgan, GRL 1997). However, in order for the pressure gradient to be felt over a region 100's of km wide, the mantle has to be very stiff. Otherwise, viscous flow of the solid would dissipate the required pressure gradient. It turns out that the required mantle viscosity, ~ 10^{21} Pa s, is substantially higher than that estimated for the Earth's upper mantle.

A second hypothesis, illustrated in the righthand diagram, is that partial melt within the upwelling mantle lowers the density of the rising column of peridotite, giving rise to buoyancy driven, "active upwelling" of partially molten mantle peridotite (Nicolas & Violette Tectonophys 1982; Rabinowicz et al. EPSL 1984;Crane EPSL 1985; Whitehead et al. Nature 1985; Buck & Su, GRL 1989). Very narrow, diapiric upwelling of this kind – required to explain focused crustal accretion in a zone a few km wide – would give rise to average degrees of melting much higher than observed for MORB (Spiegelman, EPSL 1996).

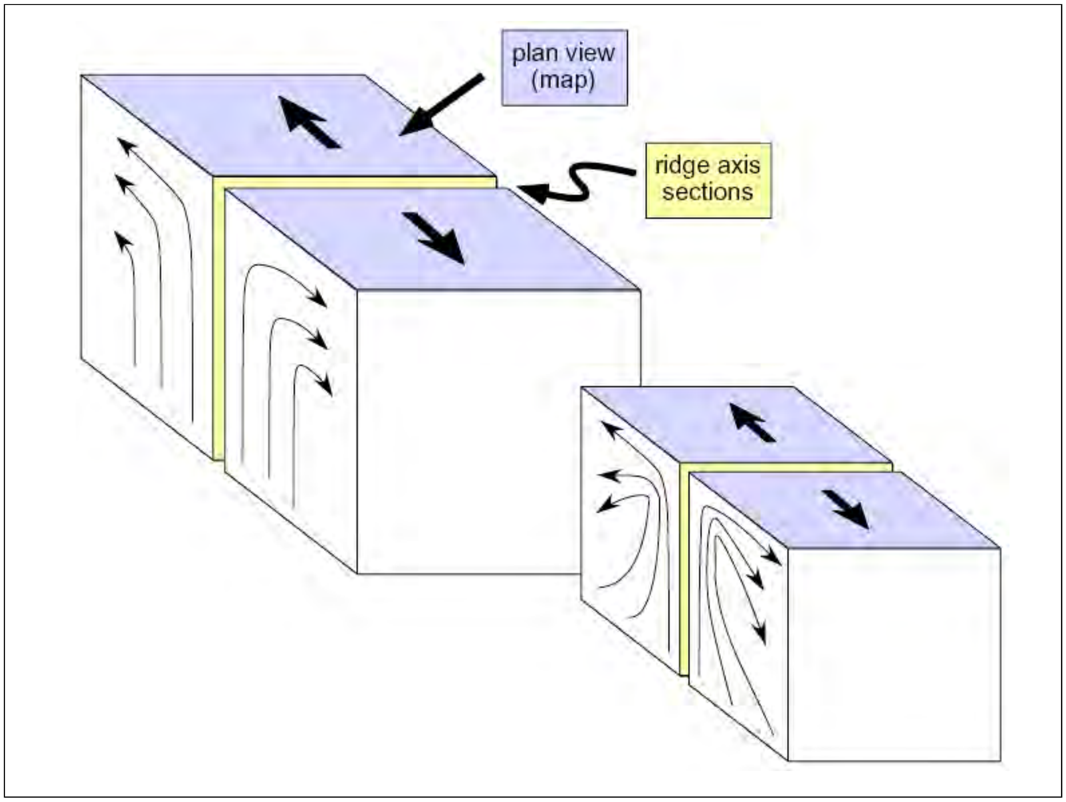
relatively shallow melt focusing beneath a permeability barrier near base of thermal boundary layer?



A third possible explanation for focusing of melt flow from the mantle toward a spreading ridge is that transport in the mantle melting region beneath ridges is dominantly vertical, but flow is deflected toward the ridge beneath a permeability barrier created by crystallization in pore space where melt begins to enter the conductively cooled, shallow mantle (Sparks & Parmentier, EPSL 1991; Spiegelman Phil Trans Roy Soc London 1993; Ghods & Arkani Hamed GJI 2000).

This hypothesis is problematic because quantitative calculations indicate that at least half of the melt formed in the mantle will be lost by crystallization in the conductive boundary layer, which is inconsistent with geochemical and geophysical estimates of the amount of melting beneath ridges and the amount of igneous crust formed at ridges.

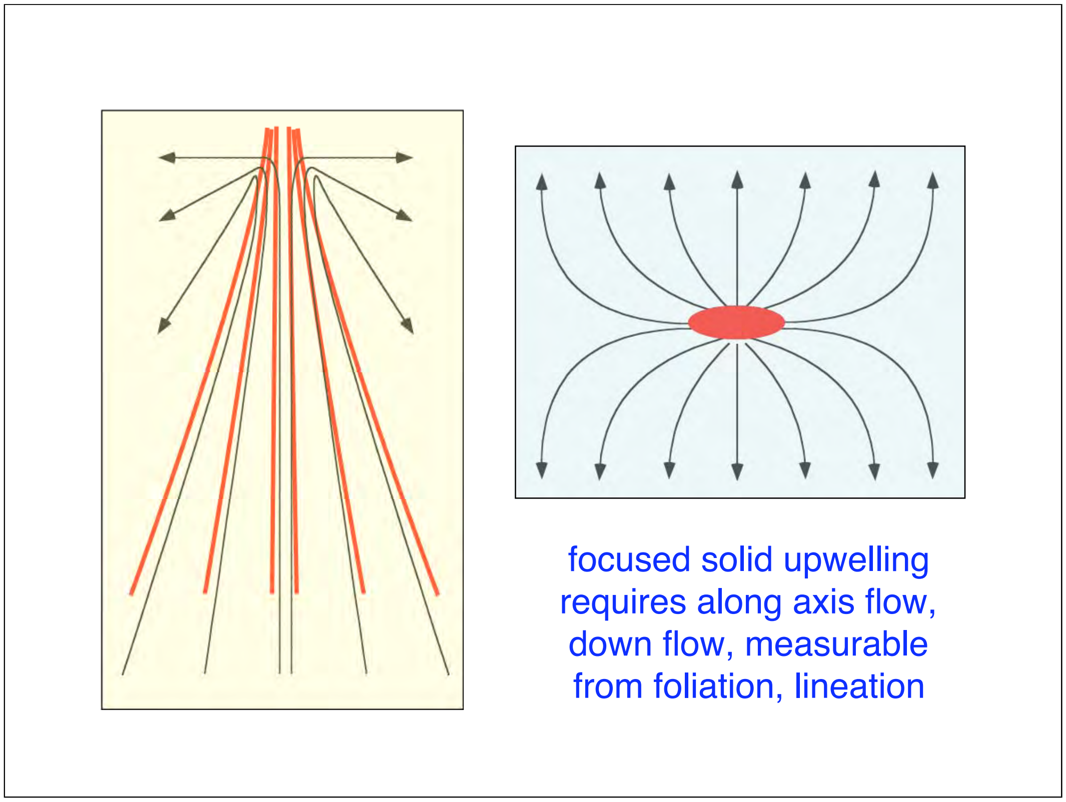
Figure from Spiegelman PTRSL 1993



The patterns of mantle and melt flow are very distinct for the different hypotheses, as schematically illustrated here.

Passive, plate driven mantle upwelling produces a 2D pattern of flow perpendicular to the ridges as shown in the upper left. Bouyancy driven, active or diapiric mantle upwelling produces a pattern such as shown in the lower right. The pattern of foliation versus depth in samples of the shallow mantle may allow us to distinguish between these possibilities.

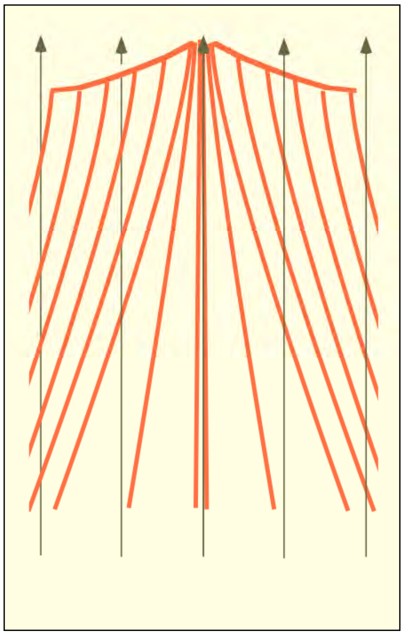
Figures from drilling proposal for ODP Leg 209

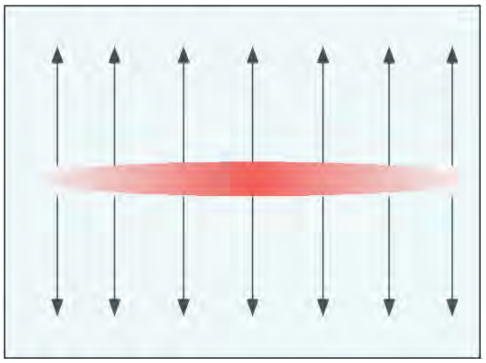


focused solid upwelling
requires along axis flow,
down flow, measurable
from foliation, lineation

This slide shows a ridge parallel vertical section (yellow background) and a map view (blue background). Melt flow (red) and solid flow should be focused toward the center of ridge segments at depth, and radially away from the center of ridge segments at shallow levels. This could be revealed as consistent, ridge parallel lineation (spinel shapes, olivine a-axes) in shallow mantle peridotite.

Will a record of ridge parallel solid flow be retained in deformed mantle peridotites from the shallow mantle beneath Pacific crust?



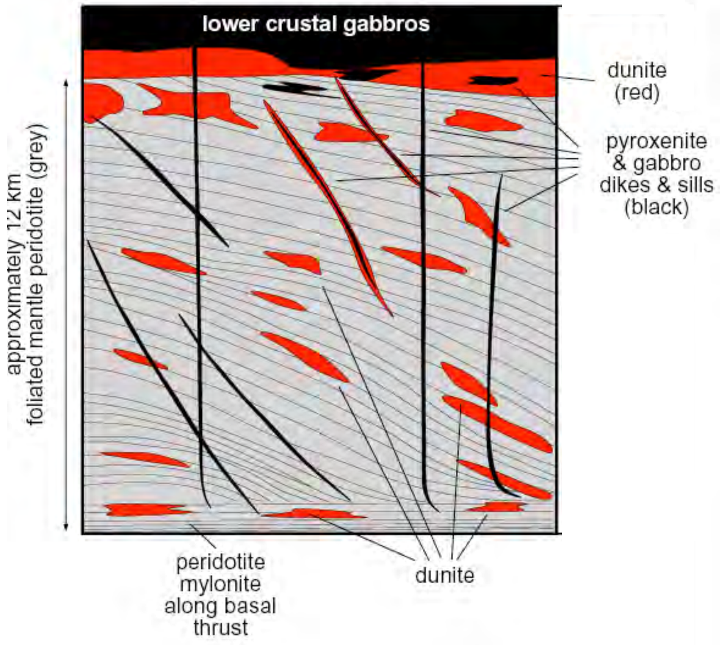


focused melt transport
requires specific vein
&/or dike orientations

In contrast, passive mantle upwelling should produce essentially 2D flow in residual peridotites, with no along axis component, and increasingly shallow melt transport features toward segment centers.

If shallow mantle peridotites beneath Pacific crust show ridge perpendicular flow features (spinel elongation and olivine crystallographic a-axes aligned parallel to the plate spreading direction), this will be an indicator that mantle flow at the EPR is not focused in three dimensions.

schematic mantle section
Oman ophiolite

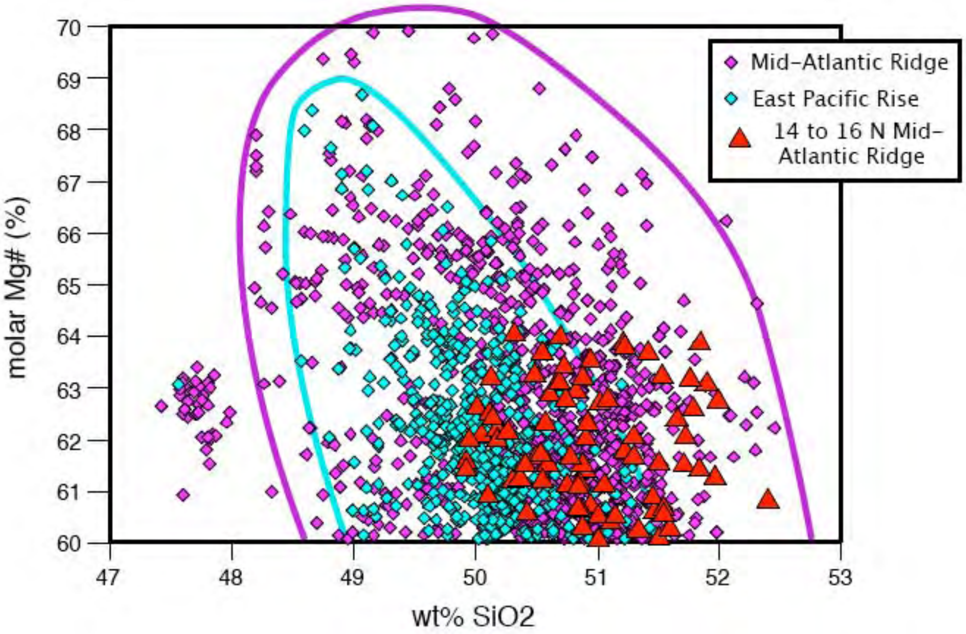


Mapping of melt transport features in ophiolite mantle sections, and sampling via drilling, can shed light on melt transport as well as solid deformation processes. Most of the mantle section in the Oman ophiolite has nearly horizontal mantle foliation, sub-parallel to the crust mantle boundary and the paleo-seafloor. This is interpreted as having formed by transposition during corner flow beneath the ridge.

In the past, gabbroic and pyroxenite dikes (black, cross-cutting features in the schematic cross section) were interpreted as the traces of melt transport through the shallow mantle to form the crust. This is incorrect, at least for the Oman mantle section where most dikes have compositions that are not in equilibrium with the melts that formed lavas, sheeted dikes, and lower crustal gabbros in Oman, and are not in equilibrium with MORB (e.g., Kelemen et al. Phil Trans Roy Soc London 1997). In the Oman ophiolite, gabbroic rocks in equilibrium with MORB-like melts are found only in the crust and in the shallowest 500 to 1000 m of the mantle section (e.g., Benoit et al MGR 1996; Kelemen et al EPSL 1997; Ceuleneer & Python G-cubed 2003).

The only melt transport features in the Oman mantle section which formed during migration of the melt that formed the igneous crust in Oman are dunites, rocks composed only of olivine and minor amounts of spinel (shown in red). As seen in the schematic cross-section, dunites in Oman are generally tabular bodies sub-parallel to the transposed mantle foliation. They have undergone some sub-solidus, plastic deformation along with their host peridotites, and thus are thought to have formed in the upwelling mantle beneath the Oman spreading ridge, and then undergone corner flow along with host peridotites.

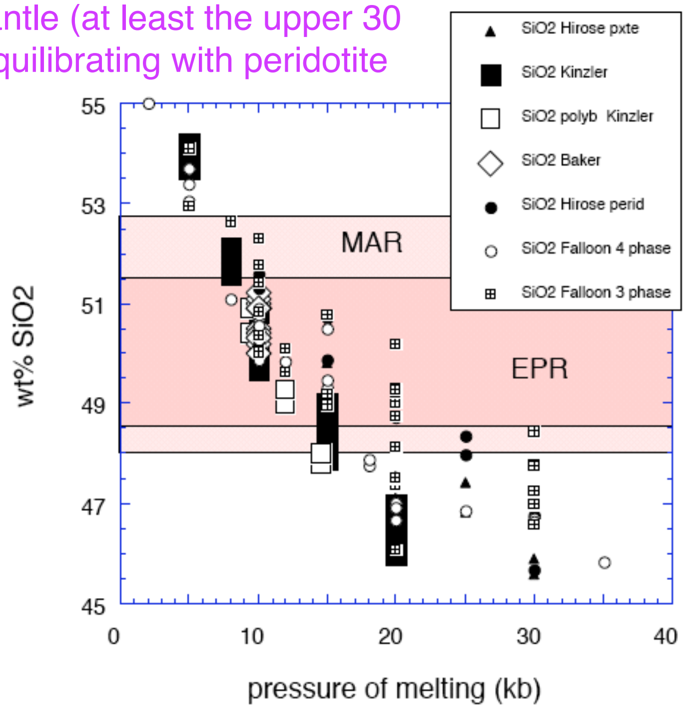
Alternatively, recent workers have suggested that perhaps some dunites formed in a sub-horizontal orientation, after corner flow of the host peridotites, beneath a permeability barrier formed by crystallization in the shallow, conductively cooled mantle (e.g., Sohn & Sims Geology 2005; Rabinowicz & Ceuleneer EPSL 2005). This is a crucial distinction, and this hypothesis needs to be tested.



SiO2 versus Mg# (molar MgO/(MgO+FeO) with all iron as FeO) in primitive MORB glasses from the North Atlantic and the EPR north of the equator. In the Atlantic, some of the extension to relatively high SiO2 may be related to shallow reaction between rising melt and conductively cooled, shallow mantle peridotite. Low SiO2 glasses come from an "ocean island basalt" component near the Azores. Northern EPR MORB show a more restricted range of SiO2 contents, which can be interpreted in terms of melting and melt extraction processes, as illustrated in the next slide.

Illustration from Kelemen et al., ODP Leg 209 Initial Reports

http://www-odp.tamu.edu/publications/209_IR/209ir.htm somehow, primitive MORB passes through the shallow mantle (at least the upper 30 km) without equilibrating with peridotite



This diagram – based on the compilation of experimental mantle melt compositions by Kelemen & Holbrook (JGR 1995) – summarizes experimental data on the composition of partial melts in equilibrium with mantle olivine and pyroxene, plus plagioclase, spinel or garnet. The SiO2 content of mantle melts increases with decreasing pressure. Melt ascending through the mantle will maintain equilibrium with peridotite by dissolving pyroxenes and precipitating olivine, increasing the SiO2 content of the resulting melt to the equilibrium value at a given pressure.

The pink bands show the range of SiO2 contents in primitive MORB, with Mg# > 60%, from the previous slide. Melt in equilibrium with mantle olivine has Mg# > 65%. Small amounts of crystallization of olivine (with or without plagioclase and pyroxenes) from mantle derived melts lead to constant or increasing SiO2. We use primitive glass compositions in an attempt to filter out more extensive changes in SiO2 due to extensive crystal fractionation, and thus to determine upper bounds on the SiO2 content of melts passing from the mantle into the oceanic crust.

Globally, MORB close to Mg# equilibrium with mantle peridotite has < 52.5 wt% SiO2. Along the northern EPR, primitive MORB has less than 51.5 wt% SiO2. This indicates that primitive MORB in the Pacific last equilibrated with mantle peridotite at a pressure > 10 kb (30 km). In turn, this requires some mechanism of focused melt transport that can preserve disequilibrium between ascending melt and surrounding peridotite from more than 30 km to the surface.

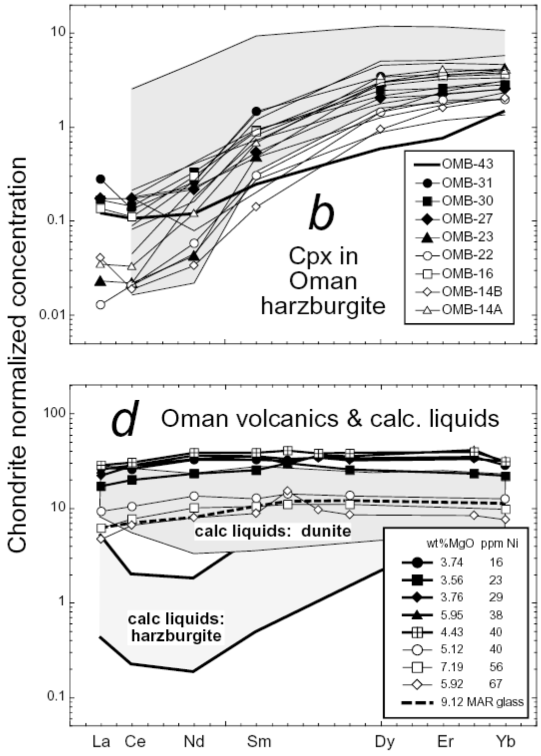
Conduits composed of dunite have the geometrical, mineral and chemical characteristics required to satisfy these constraints (Quick, CMP 1981; Kelemen, J Geol 1986, J Petrol 1990; Kelemen et al. JGR 1995, Nature 1995, PTRSL 1997, G-cubed 2000; Braun & Kelemen, G-cubed 2002). Melt in dunites that are wider than the distance for SiO2 diffusion during the time of melt transport (more than 1 m wide; Braun & Kelemen, G-cubed 2002) can preserve high pressure SiO2 contents. Trace elements in dunites in the mantle section of the Oman ophiolite indicate equilibrium with the melt that formed the crust in the ophiolite, which in turn was almost identical to MORB (Kelemen et al., Nature 1995).

dunites: tan, residual peridotites: brown

This photograph of the Oman ophiolite mantle section, shows tan dunites within brown residual peridotites, with a castle for scale. The dunites are generally parallel to the foliation in host peridotite, the dunites have been ductilely deformed together with the host peridotites, and the dunites intersect at acute angles, consistent with large shear strains. For this reason, they have been interpreted as having formed in the upwelling mantle beneath the Oman spreading ridge, and having undergone transposition to a sub-horizontal orientation, along with host peridotites, during corner flow.

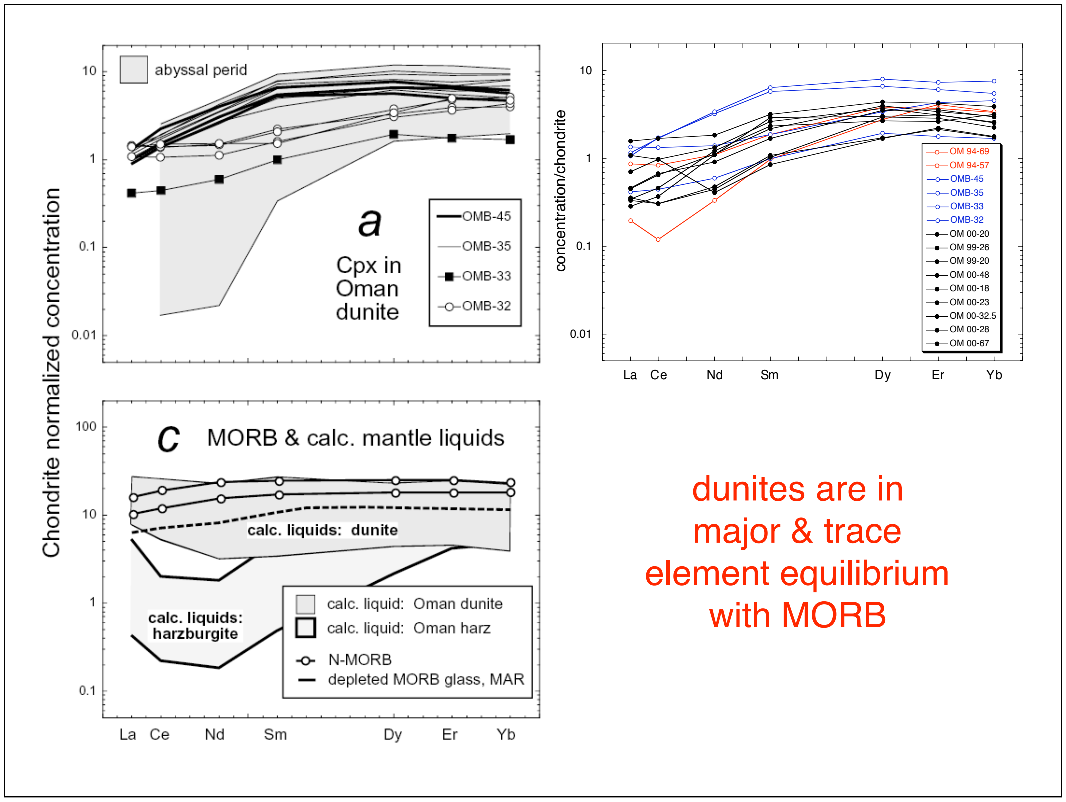
residual peridotites are out of trace element as well as major element equilibrium with MORB:

provides a convenient way of identifying veins and dikes that ARE in equilibrium with MORB



Trace elements in Oman residual peridotites (symbols in upper panel) and most abyssal peridotites (grey field in upper panel) can be inverted to yield equilibrium melt compositions (calc liquids: harzburgites, in lower panel). These compositions are very different from the liquids that formed the crust in Oman and with primitive MORB (symbols in lower panel).

Diagrams from Kelemen et al. Nature 1995



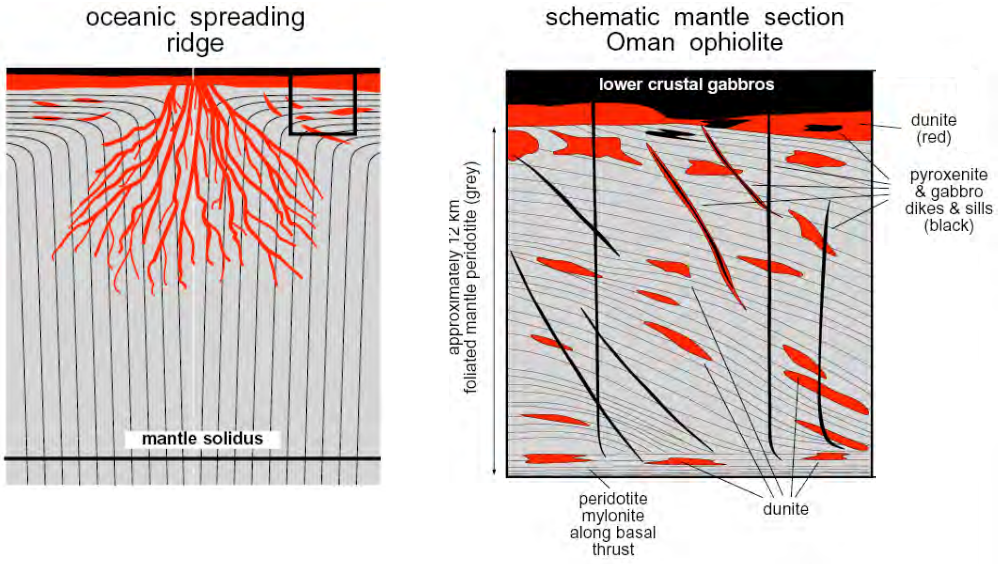
dunites are in major & trace element equilibrium with MORB

Trace elements in Oman dunites (symbols, upper panels) can also be used to calculate equilibrium liquids. In contrast to the equilibrium liquids calculated for depleted residual peridotites (calc liquids: harzburgite), liquids in equilibrium with Oman dunites have the same trace element concentrations as the melts that formed the Oman crust and primitive MORB.

Left panels: diagrams from Kelemen et al. Nature 1995. Upper right, data from Braun & Kelemen, in prep., based on Mike Braun's thesis, WHOI/MIT Joint Graduate Program, 2002.

relatively deep coalescence of dunite network?

if so, dunites should be deformed (including sub-solidus) and intersect at low angles

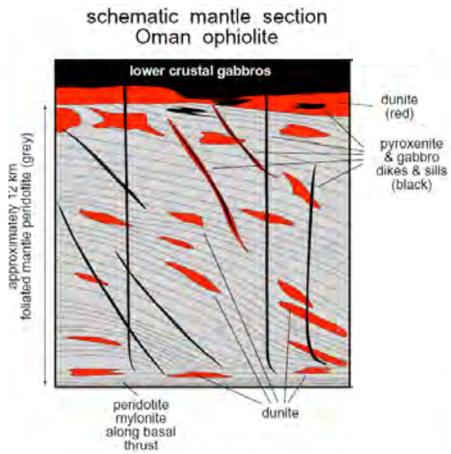


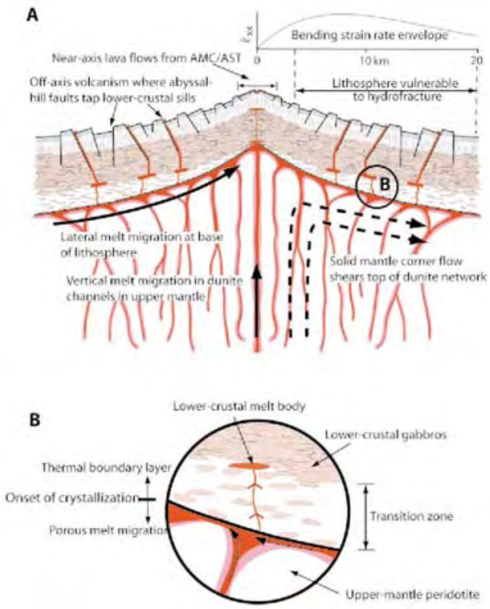
One interpretation of the distribution of dunite veins in the residual mantle section of the Oman ophiolite (and other, similar ophiolites) is that the dunites form as high porosity dissolution channels at a depth of 30 to 50 km beneath a spreading ridge, in a coalescing network of dunite conduits that focus porous flow (Kelemen et al. JGR 1995, Nature 1995, PTRSL 1997; Aharonov et al. JGR 1995; Spiegelman et al. JGR 2001). This network is then transposed and deformed during corner flow, along with host peridotites. This interpretation is consistent with the observation that many (most? all?) dunites have undergone ductile deformation along with host peridotites, are sub-parallel to the crust-mantle boundary, and show low intersection angles.

Figure from Kelemen et al. Nature 1995.

relatively shallow coalescence of dunite network?

if so, some dunites should be undeformed (including sub-solidus) and intersect at high angles

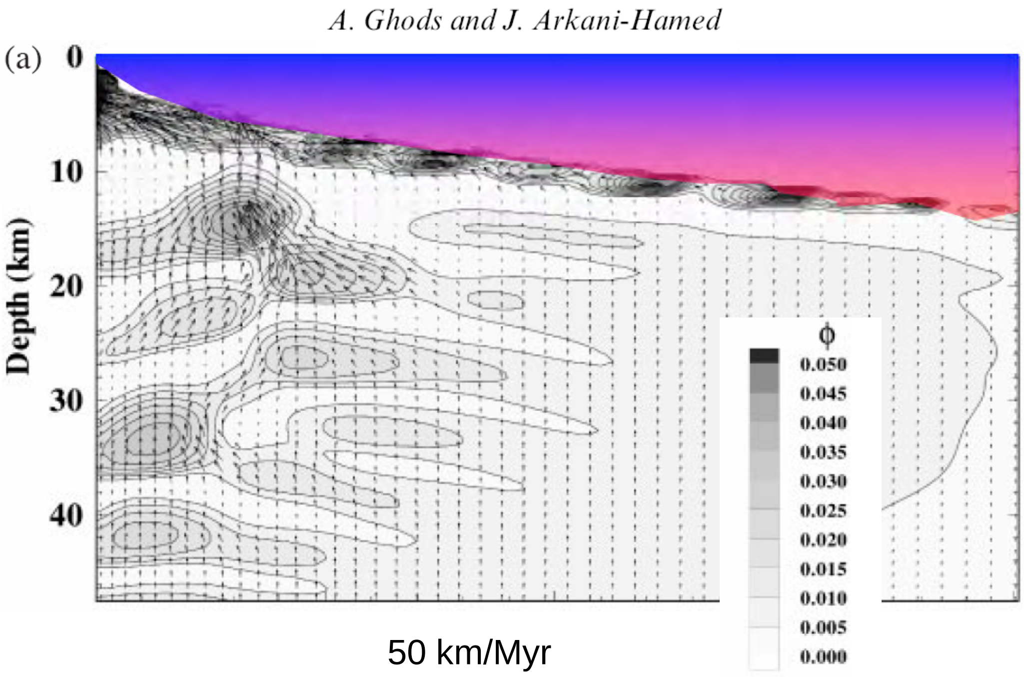




As already illustrated in a previous slide, the presence of a low permeability, inclined “freezing front” may help to focus melt flow toward oceanic spreading ridges (Sparks & Parmentier EPSL 1991; Spiegelman PTRSL 1993; Ghods & Arkani Hamed GJI 2000). An alternative interpretation of dunite distriribution in ophiolites is that some dunites form as high porosity conduits sub-parallel to a “freezing front” at the base of the conductively cooled, uppermost mantle (Sohn & Sims Geology 2005; Rabinowicz & Ceuleneer EPSL 2005). In this case, as shown on the right, we would expect to see some undeformed dunites that cut the transposed, residual mantle foliation at a high angle, plus high angle intersections between steep and sub-horizontal dunite conduits. Such evidence appears to be rare in the case of the Oman ophiolite (schematic cross-section at left), but perhaps there are anomalous structural relationships in the Oman upper mantle section. Observation of dunite distribution in a direct sample of tectonically intact, shallow mantle from beneath a Pacific ocean crustal section would resolve these questions.

Figures from Kelemen et al. Nature 1995 (left), Sohn & Sims Geology 2005 (right)

should see “impregnated”, low permeability lid above dunites



50 km/Myr

In addition, if the idea of a permeability barrier at the base of the conductively cooled, uppermost mantle is valid for focusing of melt to the East Pacific Rise, then we should observe abundant evidence for crystallization of melt in pore space in the shallow mantle beneaeth Pacific crust, corresponding to the colored region in the diagram above.

Figure from Ghods & Arkani Hamed, GJI 2000.

spatial statistics on melt transport features provide insight on network structure and method of extrapolating to larger scales

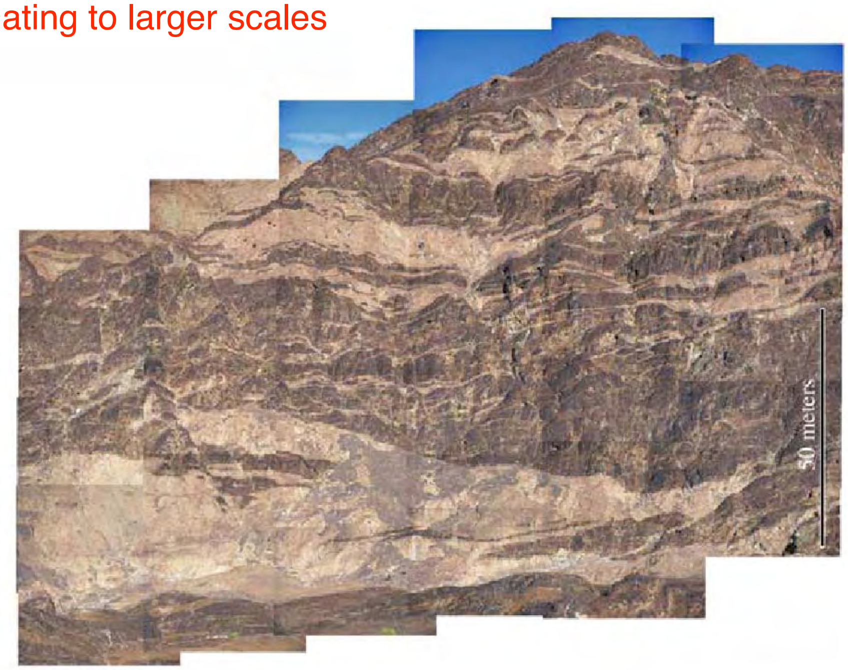
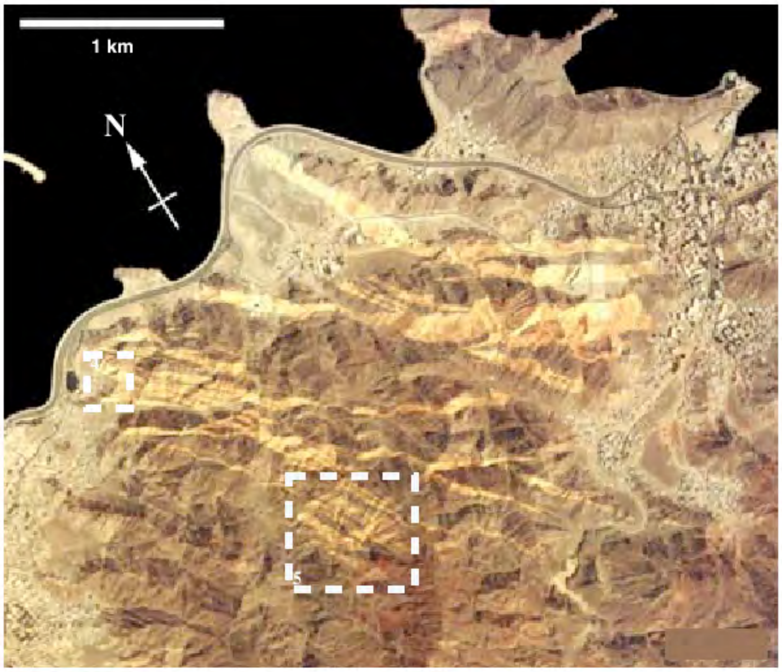


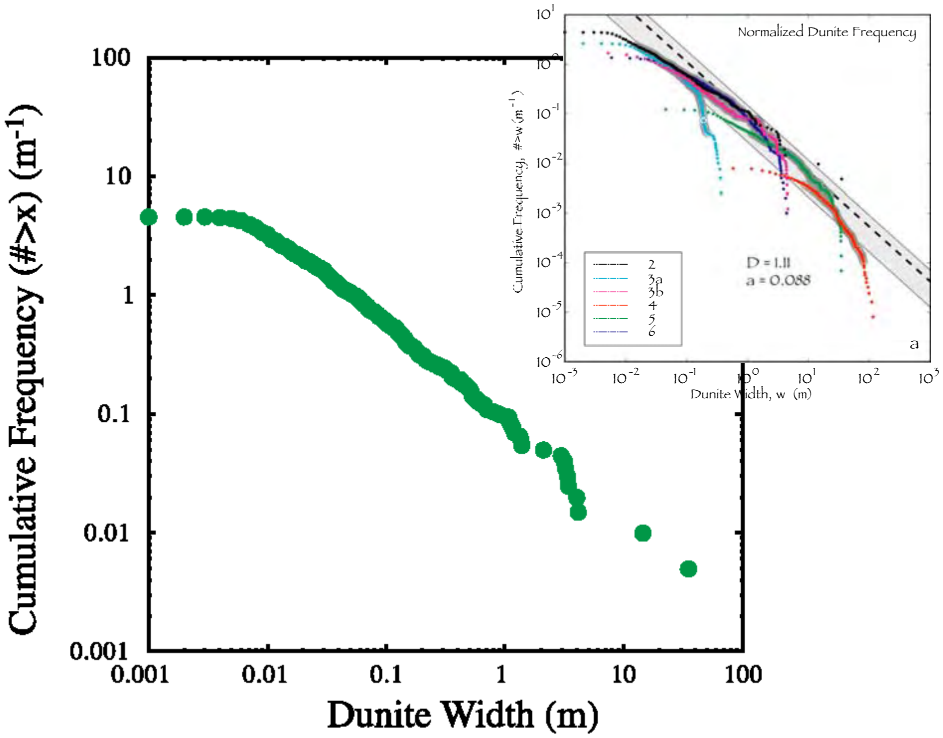
Photo mosaic of an outrop of tan dunites in brown residual mantle peridotites from the Oman ophiolite. 50 meter scale bar on right.

Figure from Braun & Kelemen, G-cubed 2002.



Air photo of tan dunites in brown residual mantle peridotites in Oman near the capital city of Muscat. Dashed rectangle shows area covered in photo in the previous slide. The largest dunite in this image, in the upper right part of the outcrop area, has a true thickness (perpendicular to contacts) of 100 m, and a length exceeding 3 km.

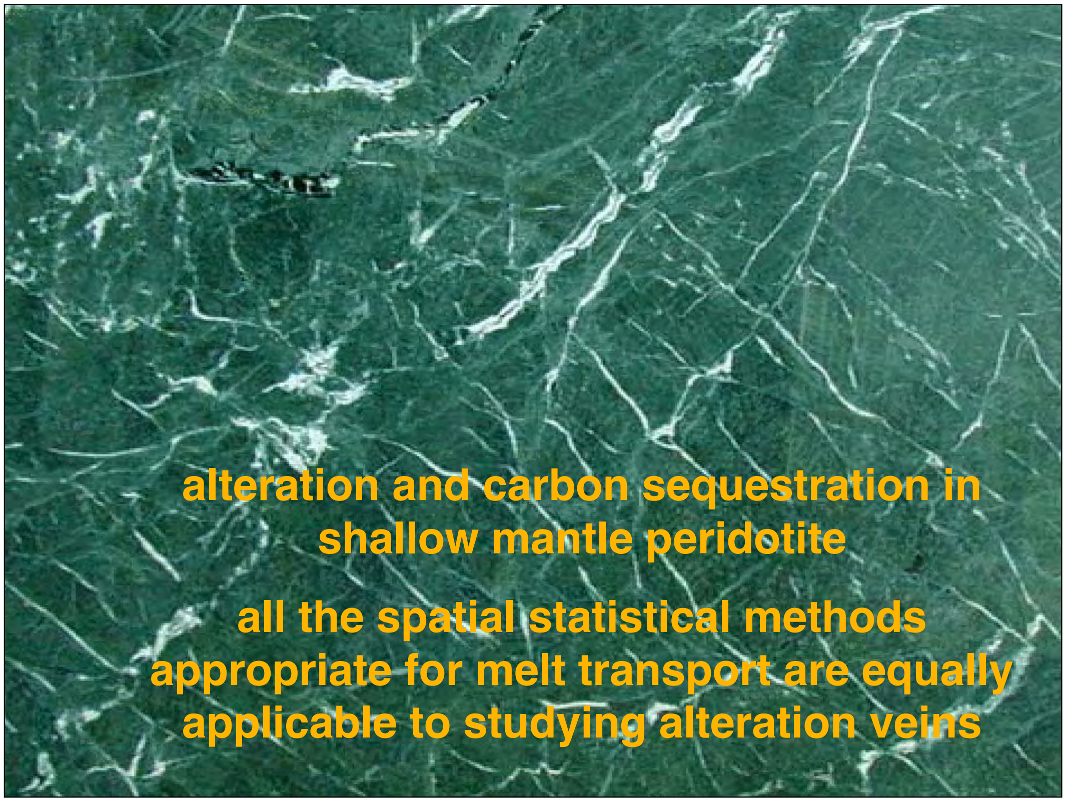
Figure from Braun & Kelemen, G-cubed 2002



Coalescing fluid transport networks generally have a few large conduits fed by many small ones, with a power-law or “fractal” size frequency distribution. Evidence from ophiolites (here, from the Oman ophiolite) demonstrates that tabular dunites within residual mantle peridotites show this kind of size-frequency distribution (Kelemen et al. G-cubed 2000; Braun & Kelemen, G-cubed 2002), consistent with their inferred role as a coalescing melt transport network.

There are no comparable data sets from modern mid-ocean ridges, and since the spreading rate and tectonic significance of ophiolites is unknown, we have no direct information on the mode of melt transport in the shallow mantle beneath mid-ocean ridges, especially in the Pacific where tectonic exposures of peridotite are very rare. Even at Hess Deep, where EPR mantle is tectonically exposed, tectonic rotation of fault blocks renders structural interpretation of dunite orientation and frequency almost impossible.

Drill core from the shallow mantle beneath intact EPR crust would allow scientists to measure the spatial distribution and orientation of melt transport structures, and the orientation of ductile flow indicators, and thus produce unique, strong constraints on all of the outstanding problems in mantle and melt flow outlined in the second half of this presentation.



alteration and carbon sequestration in shallow mantle peridotite

all the spatial statistical methods appropriate for melt transport are equally applicable to studying alteration veins

All samples of the oceanic upper mantle are substantially altered by interaction with seawater. In ophiolites, along slow spreading ridges, and in tectonically dismembered EPR mantle samples, it is not clear whether this alteration occurs at depth, or as a result of the anomalous tectonic processes that locally bring mantle peridotite to the seafloor.

Alteration of mantle peridotites is a very important process, both geophysically and geochemically. Geophysically, partially serpentinized mantle peridotite can have density, Vp and Vs indistinguishable from gabbroic rocks, rendering it difficult to determine IGNEOUS crustal thickness – and thus, magma fluxes at ridges – from seismic data. Direct sampling of the shallow mantle, together with seismic experiments in ths same region, can provide crucial data to help resolve this problem. In addition, many workers attribute intermediate depth earthquakes – which can be large and destructive – to dehydration of serpentine in subducting mantle peridotite. Data on the extent of serpentinization of the oceanic upper mantle are essential to evaluate this hypothesis.

Geochemically, serpentinization of peridotite provides a source of H_2O for the fluids and melts that form the “subduction component” in arc magmas. The subduction component distinguishes arc from mid-ocean ridge magmas, and has end-member characteristics similar to continental crust, suggesting that the subduction component is essential to formation of continental crust. Estimates for the efficiency of H_2O recycling in subduction zones depend on untested assumptions about the extent of serpentinization of the shallow mantle beneath oceanic crust, which would be tested by drilling.

Serpentinization is often accompanied by carbonation of shallow mantle peridotite. For example, the white veins in the diagram above are veins of magnesite ($MgCO_3$) and calcite ($CaCO_3$) in a matrix of serpentinized peridotite (field of view approximately 3 meters wide). Carbonation of peridotite is one of the leading candidates for sequestration of anthropogenic, atmospheric CO_2 in stable, solid form. A key to evaluating the suitability of such a process is understanding the mechanism and kinetics of natural peridotite sequestration. At present, there are few if any data on the large scale proportion of CO_2 in altered, oceanic upper mantle, or the rates of peridotite carbonation in these settings.

Samples of the shallow mantle from beneath tectonically intact EPR crust would resolve the question of how much, if any, alteration occurs at the base of fast-spreading crust, and what proportion of CO_2 is incorporated into these rocks. Methods illustrated in previous slides, for spatial and chemical characterization of alteration and melt transport veins, could be used in exactly analogous fashion to study the mechanism of serpentinization and carbonation.

Finally, most workers expect the extent of alteration in the shallow mantle to be much less beneath tectonically intact EPR crust compared to slow-spreading crust or tectonic exposures of peridotite in the Pacific. Where mantle $Vp > 8$ km/s in a broad region beneath the EPR, we can expect to recover nearly fresh mantle peridotite, almost completely free of alteration.

We currently have no fresh samples of the mantle residue beneath oceanic crust. Such samples would be nearly equivalent to samples from the Moon or Mars, in terms of the difficulty of obtaining them, and in terms of their geochemical import. For example:

(1) Determining the concentration and mineral hosts for S, C and He in fresh residual peridotite samples would help resolve the open questions of whether shallow residues of MORB formation are sulfide saturated, CO_2 saturated, and He saturated. These in turn have bearing on the solid/liquid partitioning of these species during melting on Earth and other planets. None of these can be determined using altered samples, peridotite massifs, or xenoliths.

(2) Fresh residual peridotite samples would also provide unique data on the extent to which MORB is in isotopic equilibrium with residual peridotite, or instead includes a substantial component derived from melting of eclogite or pyroxenite veins derived from recycling of ancient crustal material (e.g., Salters & Dick Nature 2002).

(3) Estimates of the modal proportion of minerals in the MORB residue, and thus the composition of the MORB source, are greatly complicated by differential volume change during alteration (e.g., Niu J Petrol 1997; Baker & Beckett EPSL 1999), and fresh shallow mantle samples would resolve this problem.

(4) Enrichment in highly incompatible elements is ubiquitous in dredged samples of residual peridotite from ridges (e.g., Niu J Petrol 2004), but it is unclear whether this enrichment arises via grain boundary partitioning during melting and melt extraction (e.g., Hiraga et al. Nature 2004), “impregnation” during crystallization along grain boundaries as melt enters the conductively cooled, shallow mantle (e.g., Niu J Petrol 2004), or hydrothermal alteration (e.g., Gruau et al. GCA 1998).

lower crust

- Gabbro glacier vs sheeted sills
  - chemical layering, shape & crystal fabric
- Focused hydrothermal convection vs “enhanced conduction”
  - spatial distribution, water/rock ratio, cooling rate, age
- Off axis hydrothermal convection?
  - Porosity? Fluids now?
- Lower crustal composition:
  - Primary magmas
  - Igneous composition
  - Hydrothermal alteration
  - Global geochemical cycling
    - Re/Os, U/Pb, Th/Pb, Rb/Sr
- Deep biosphere?

Summarizing topics in red. Additional topics in blue.

upper mantle

- Bouyancy driven vs plate driven, 2D vs 3D
  - Lineation perpendicular or parallel to ridge
- Nature and age of melt transport features
  - Age, proportion, width/frequency, deformation history, orientation & intersection, assymetry
- Extent, T, and age of hydrothermal alteration
  - Cooling rates, proportions of phases, vein structure
- Composition (especially if fresh):

  Modes: unaltered vs altered

  Trace elements: LILE enrichment? U/Pb, Th/Pb?

  Volatile elements: He, H concentration, S saturated?

  Isotope ratios: comparable to lavas, or not?

Summarizing topics in red. Additional topics in blue.

That’s all, folks!

Finally …

The Hubble Space Telescope (HST) cost more than $1.5 billion to construct and launch in 1990 (some sources say about $2 billion). Additional costs were associated with its repair by astronauts from the Space Shuttle. The "First Servicing Mission" cost ~ $0.7 billion. The Second Servicing Mission cost ~ $0.35 billion for development and ~ $0.45 billion for the shuttle flight. There have been one or two more, smaller servicing missions. Thus, the telescope and its repair cost > $3 billion. The final servicing mission was cancelled, though this is still debated and might be reversed. The telescope was planned to work until ~ 2010. After a while it will fall to Earth, with some danger to people.

$3 billion over 20 years corresponds to about $1.15 per individual US tax return per year. In other terms, $3 billion is about 1/20th of US spending in 2003 for the Dept. of Education, and more than 3/5 of 2003 US spending for the National Science Foundation.

Perspective on Mohole from Current Knowledge of the Ocean Crust

Jim H. Natland

Perspective on Mohole from Current Knowledge of the Ocean Crust

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RSMAS/MGG
University of Miami
Miami, FL 33149

Photographs of (left) an outboard motor used for dynamic positioning on CUSS I and (right) CUSS I at sea. Basalt was reached on April 1, 1961 at the Experimental Mohole test site near Guadalupe Island, Mexico.

PLATE V *Harbormaster* 250-hp diesel-powered outboard motor, similar to those which will be used to power *CUSS I* during the experimental drilling. The engine is fixed but shaft and propeller can turn to exert thrust in any direction.

PLATE VI *CUSS I* during the Guadalupe Island experiments, April 1961. It successfully held position and, for the first time, drilled into the deep-sea floor.

from* Bascom (1961) *A Hole in the Bottom of the Sea

Hess's Seafloor Spreading This theoretical concept was extended to explain the observations of crustal structure of mid-ocean ridges

Left: Harry Hess;

Right: Hess's (1960) cross-section of an idealized section of ocean crust at a spreading ridge, illustrating his concept of Moho being a contact between serpentinized and fresh peridotite.

Harry Hammond Hess
1906–1969

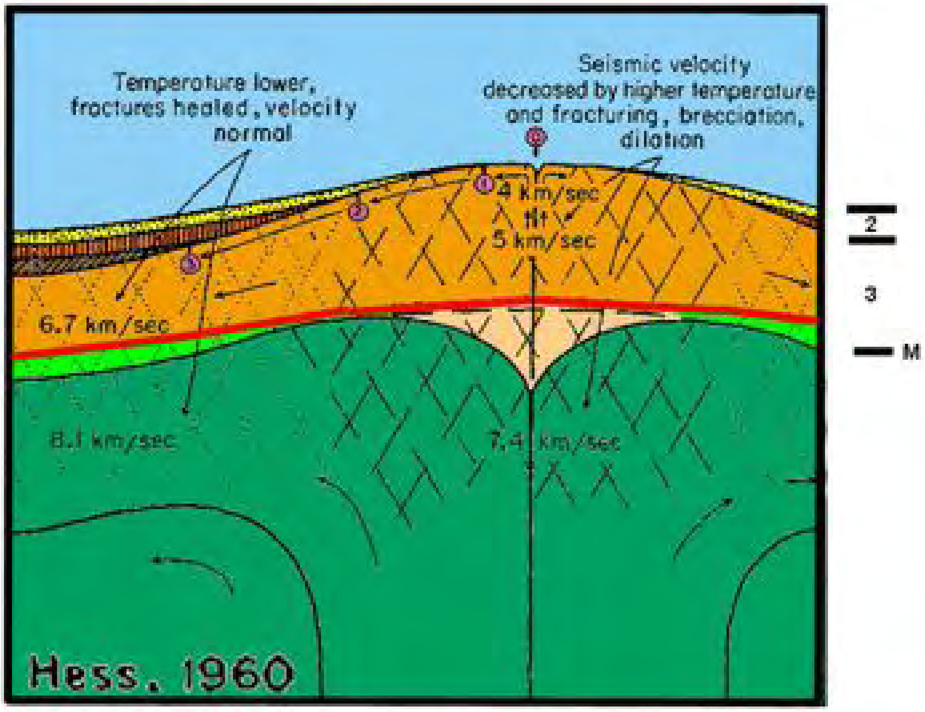


Figure 7. Diagram to represent (1) apparent progressive overlap of ocean sediments on a mid-ocean ridge which would actually be the effect of the mantle moving laterally away from ridge crest, and (2) the postulated fracturing where convective flow changes direction from vertical to horizontal. Fracturing and higher temperature could account for the lower seismic velocities on ridge crests, and cooling and healing of the fractures with time, the return to normal velocities on the flanks.

Is Moho a lithologic or chemical transition? The question still has not been answered.

spective Based on Seismic Refraction

Modern perception of the distribution of melt beneath the axis of a fast-spreading ridge, and the relationship of the layered structure of the ocean crust to it. Modified from a diagram of Sinton and Detrick.

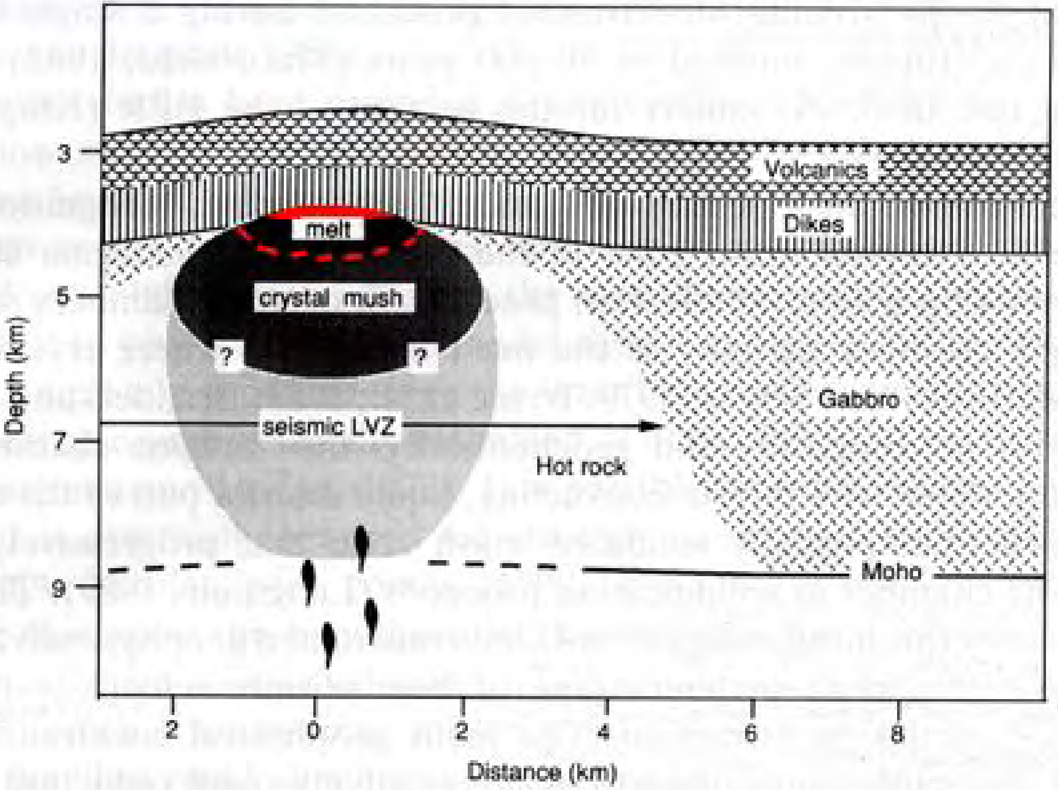


Figure 5. Interpretive model of an EPR magma chamber based on recent seismic results. The essential elements of this model are a narrow, sill-like body of melt 1–2 km below the sea floor that grades downward into a partially solidified crystal mush zone which marks the transition from the (mostly liquid) chamber interior to the largely solidified (but still hot) surrounding rock. The bulk of the axial LVZ is inferred to be composed of the slowly cooling cumulate rocks of layer 3.

Seismic structure of the crust at the axis of the East Pacific Rise showing profiles of the axial block (upper) and velocity distribution (lower). The region with velocities of ~5 km/s is a body of hot rock with some partial melt. This freezes to solid gabbro with velocities of ~ 7 km/s. From Bruce Rosendahl's dissertation.

Early Seismic Refraction Studies of the Axial Block Of the East Pacific Rise At 9N (Rosendahl, 1976)

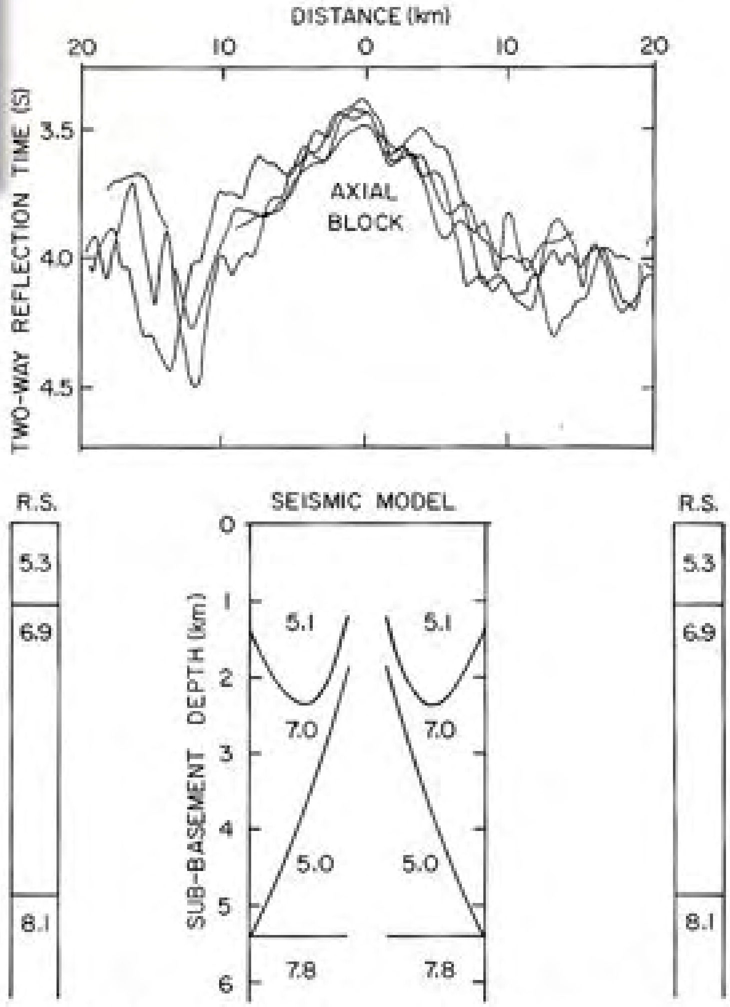


Figure 5. *Seismic refraction model of the East Pacific Rise crest (after Rosendahl, 1976). Triangular-shaped, low-velocity zone is believed to represent magma reservoir.*

Seismic Layer

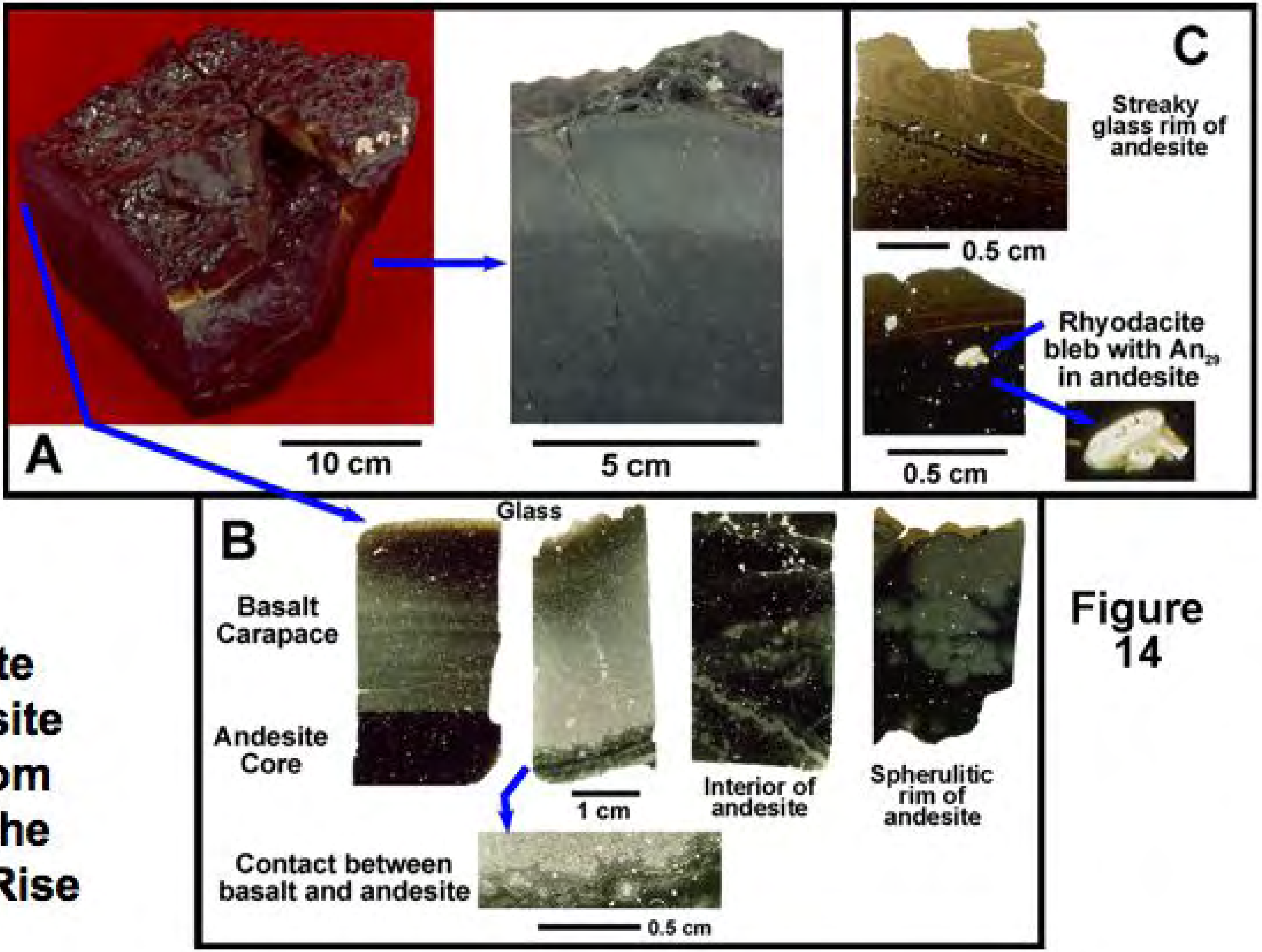
2

3

M

Dredging can recover big rocks.

I interpret the interior of this composite flow to represent highly differentiated magma occupying the axial melt lens at 9N on the EPR. It was entrained in basalt that entered the melt lens and which now forms the outer carapace of the flow.



A composite basalt-andesite lava flow from near 9N on the East Pacific Rise

Figure 14

The lower ocean crust of the fast-spreading East Pacific Rise can be studied at very few localities. One of them is at Hess Deep in the eastern Pacific. There, plutonic rocks (gabbro and peridotite) are exposed by tectonic processes acting at the tip of the westward propagating Cocos-Nazca spreading center.

Cross sections of upper and lower ocean crust are Found at Hess Deep, a rift at the end of the Cocos-Nazca Spreading Center that is propagating into the Galapagos microplate at the great Triple junction in the eastern equatorial Pacific

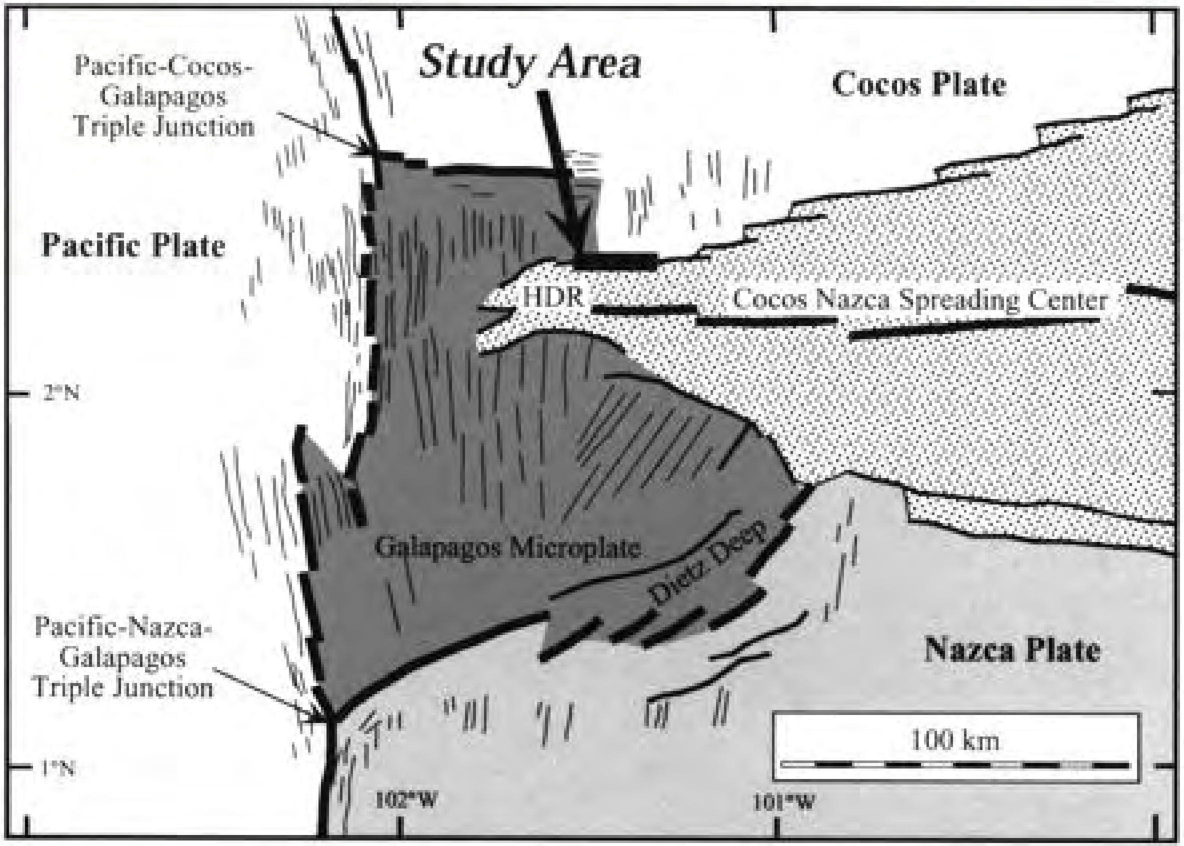
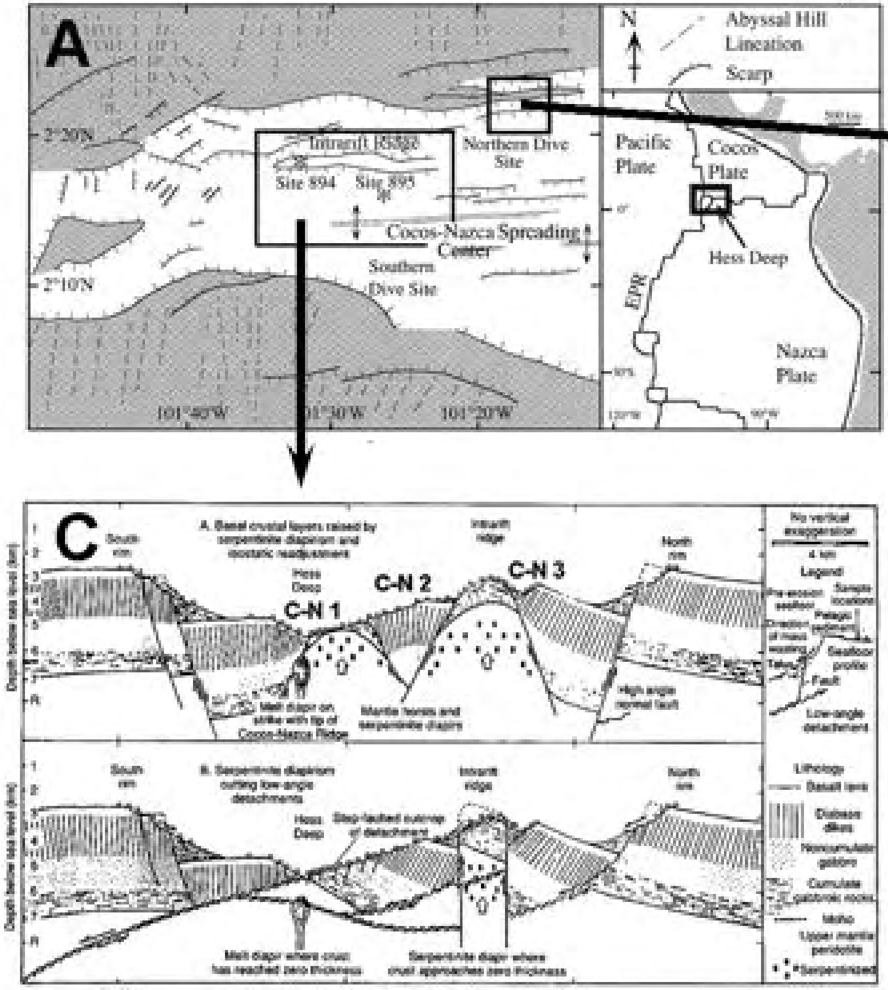


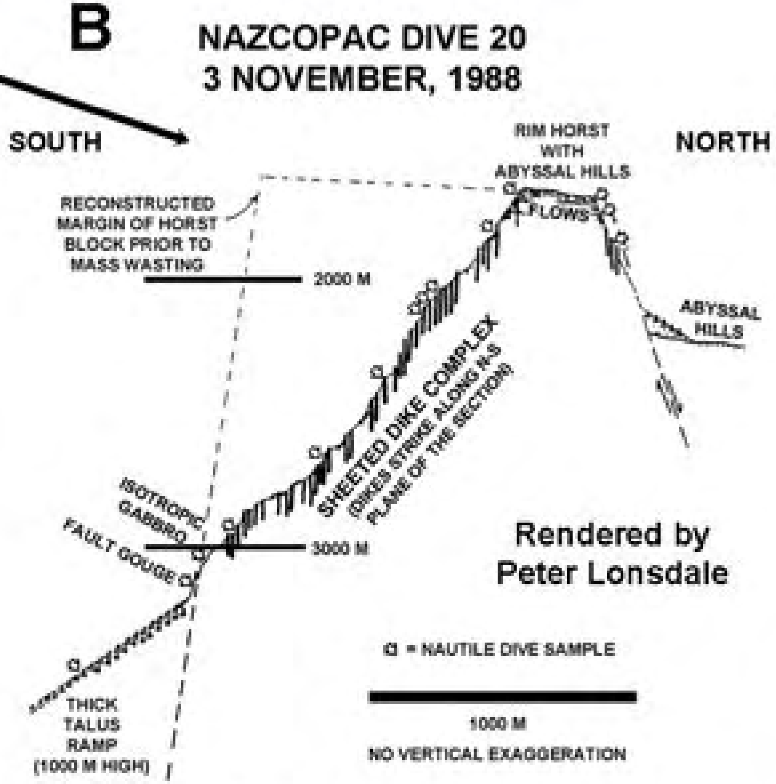
Figure 1. Location map and setting of the Hess Deep Rift (HDR). The northern rift wall is a cross section of crust formed at the East Pacific Rise (135 mm-yr-1, full rate) about 1 m.y. ago and exposed by rifting at the tip of the Cocos-Nazca propagating rift tip. Black box shows area of the Hess Deep '99 study area.

Lower ocean crust produced at the fast-spreading East Pacific Rise is exposed at the tip of the propagating rift in Hess Deep (larger area in A = C) and at an uplifted horst or block on the northern rift wall (smaller area in A = B). The uplifted block presents a coherent section downward through pillows and dikes in to upper gabbros. The section near the floor of Hess Deep presents lower gabbros and ultramafic rocks.

Figure 1



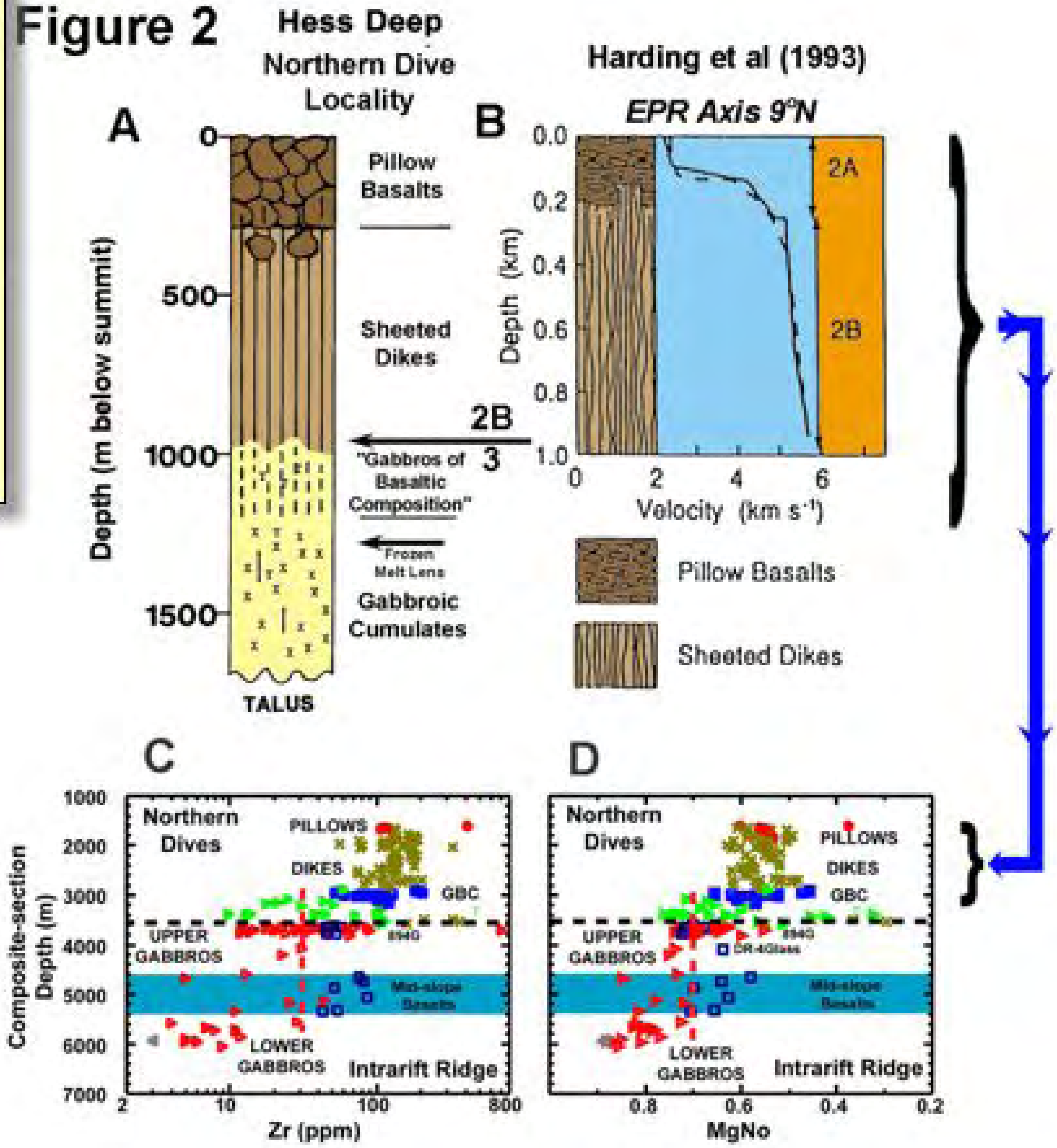
Structural Interpretations of Francheteau et al (1990)



N-S Section through the uplifted marginal horst on the northern rift wall of Hess Deep

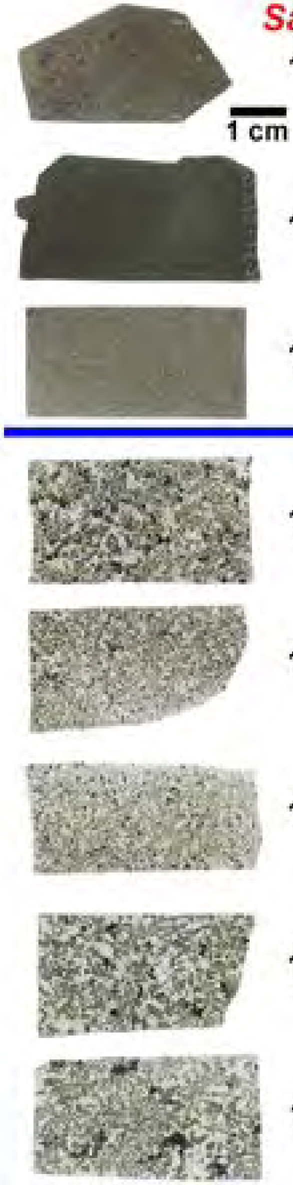
Summary of crustal structure exposed on the northern rift wall of Hess Deep (A) and in comparison with seismic stratigraphy (B). Aspects of chemistry of basalts, dikes, and gabbro cumulates are in Hess Deep composite sections that combine the northern-wall and intrarift-ridge sections (C and D). Note especially the low concentrations of Zr in gabbro cumulates (green and red triangles) and their higher MgNo than in basalts and dikes.

Figure 2



Thin section scans showing the transition downward from fine-grained aphyric basalt dikes into gabbronorite cumulates present in the section at the northern rift wall of Hess Deep.

Figure 3



Sample	*Depth*
1529	2866 m
1524	2866 m
1514	2874 m
1500	2916 m
1439	2940 m
1428	2962 m
1416	2975 m
1409	2990 m

Fine-grained Dikes

ABRUPT CHANGE IN GRAIN SIZE
1300 m beneath horst summit

Coarse-grained Base of Sheeted Dike Sequence

"Gabbros of Basaltic Composition"

Figure 4

Sample	Depth
1427	2747 m
1408	2789 m
1351	2895 m
1333	2954 m
1316	2974 m
1243	3020 m
1226	3089 m
1206	3134 m

Fine-grained Dikes

Micro-Gabbronorite

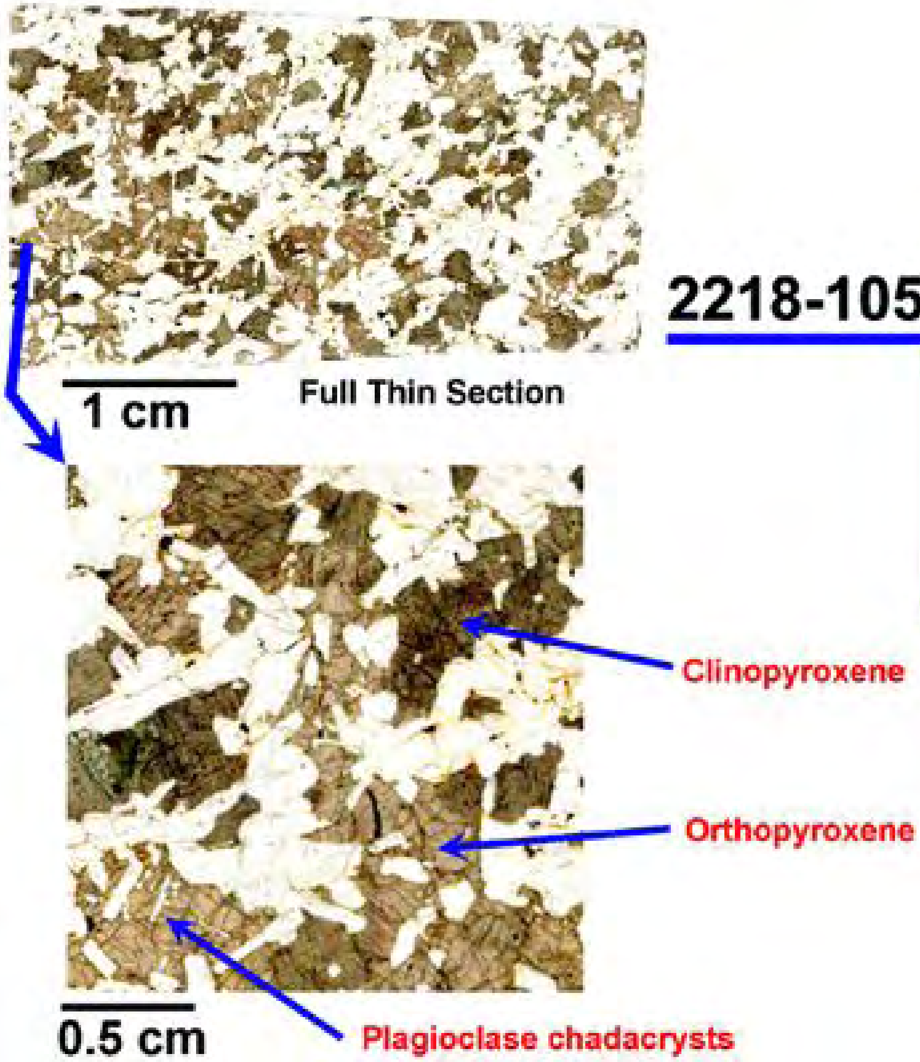
Coarse-grained Base of the Sheeted-dike Sequence

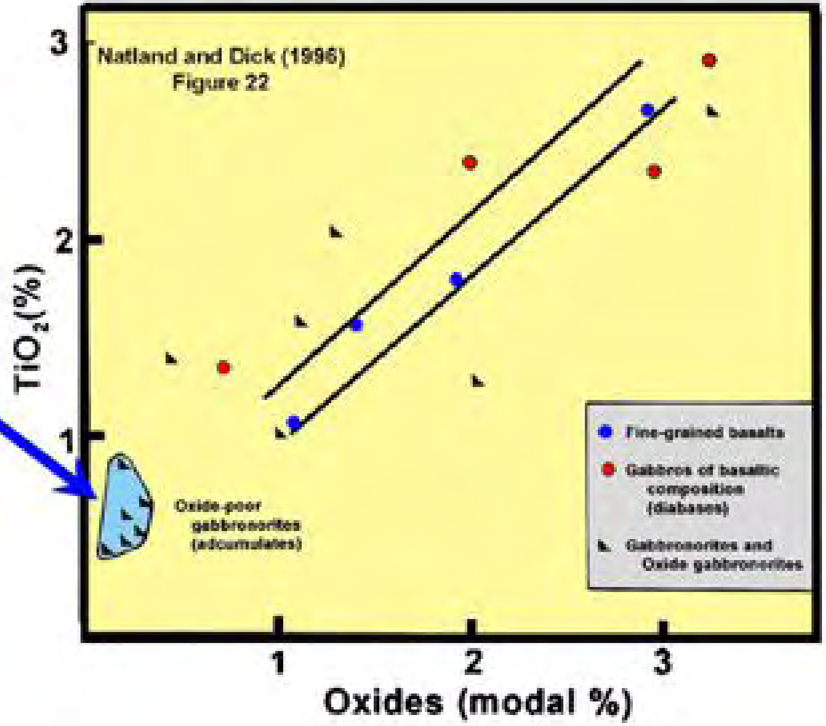
Gabbronorite Cumulates

Example of a gabbronorite cumulate from the northern rift wall at Hess Deep. Gabbro cumulates have low percentages of magmatic oxides (ilmenite and titanomagnetite), as in scanned thin sections at left, correlating with low TiO2 contents (plot at right) because interstitial melt has been expelled by compaction and continued in situ crystallization of cumulus minerals during compaction and solidification of the rocks.

Figure 6

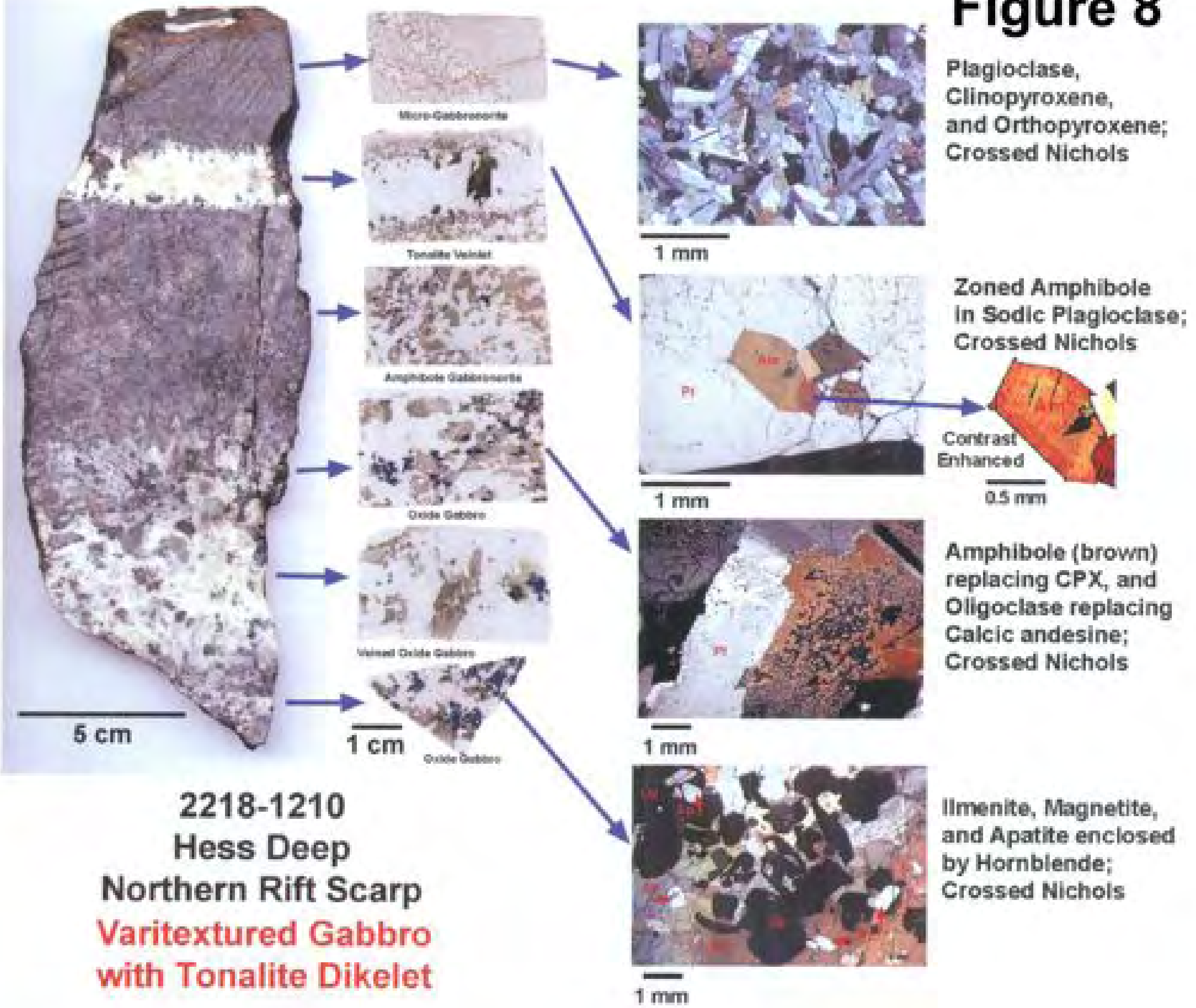
2218-1057





Varitextured gabbro at the inferred level of the melt lens, northern rift wall of Hess Deep, includes multiple lithologies even in single samples. This is a slab of a rock obtained using DSRV Alvin that contains micro-gabbronorite, coarser-grained gabbronorite, and oxide gabbro, with two tonalite-trondhjemite veins, all in a single sample about 25 cm length. The sample is oriented as in the outcrop, thus contacts of lithologies are horizontal or nearly so. From left to right, the figure shows the rock, scanned thin sections, and photomicrographs giving detailed textures. The rock has abundant magmatic amphibole (brown mineral in photomicrographs to the right.

Figure 8



Plagioclase,
Clinopyroxene,
and Orthopyroxene;
Crossed Nichols

Zoned Amphibole
in Sodic Plagioclase;
Crossed Nichols

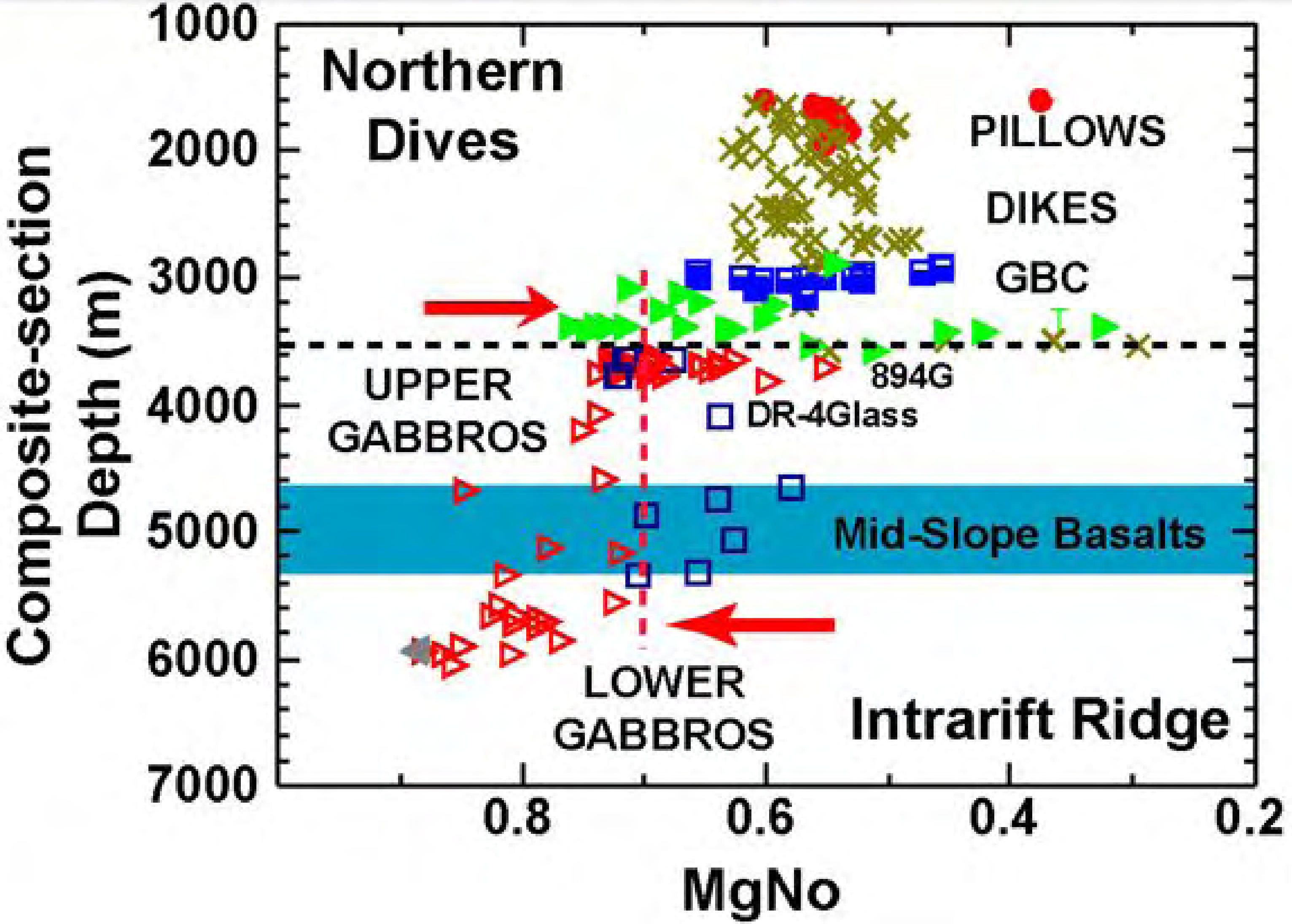
Contrast
Enhanced

Amphibole (brown)
replacing CPX, and
Oligoclase replacing
Calcic andesine;
Crossed Nichols

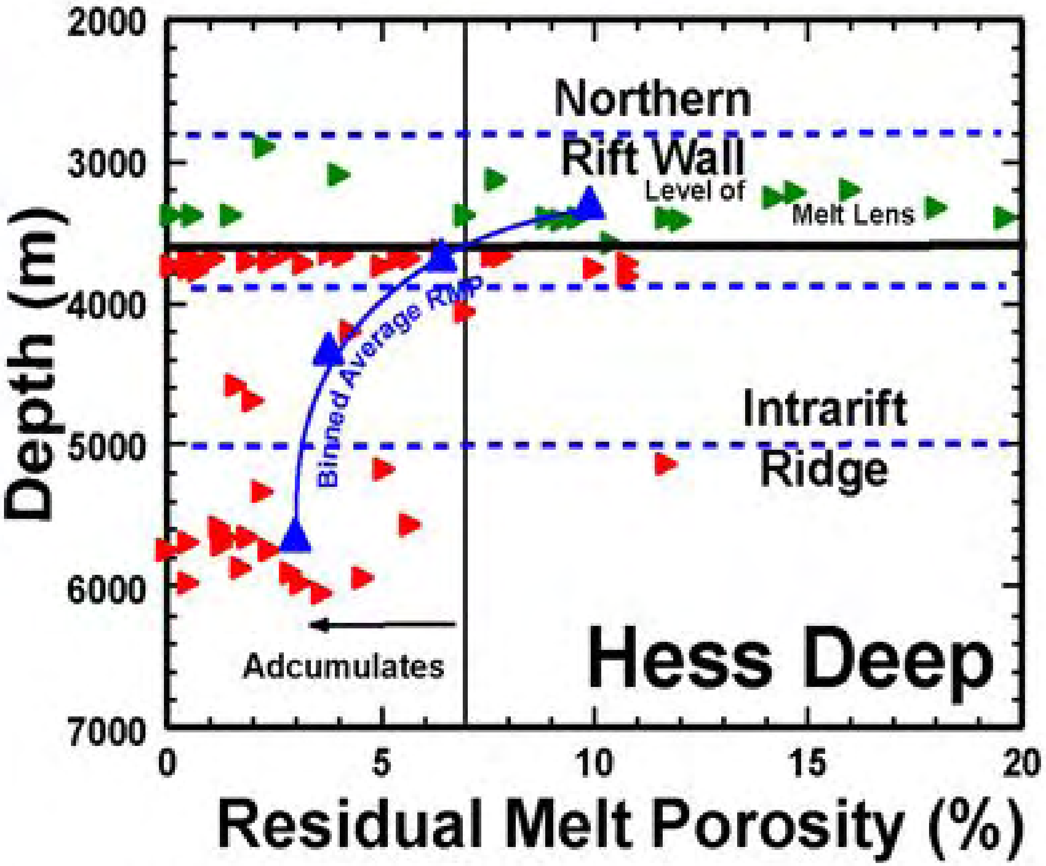
Ilmenite, Magnetite,
and Apatite enclosed
by Hornblende;
Crossed Nichols

2218-1210
Hess Deep
Northern Rift Scarp
Varitextured Gabbro
with Tonalite Dikelet

MgNo of pillows, dikes, and gabbros plotted versus composite depth of a section combining the exposure at the northern rift wall of Hess Deep, and the exposure at the Intrarift Ridge in the Hess Deep basin. Note that most gabbro cumulates have higher MgNo than basalts and dikes, but that there is great variation toward differentiated compositions (lower MgNo) among gabbros of the rift wall at the likely level of a frozen melt lens (green closed triangles) and in the uppermost gabbros of the exposure of the Intrarift Ridge, especially at ODP Site 894 (red open triangles). GBC (half-filled blue squares) = “gabbros of basaltic composition” = coarse-grained base of the dike sequence, just above uppermost gabbro cumulates.



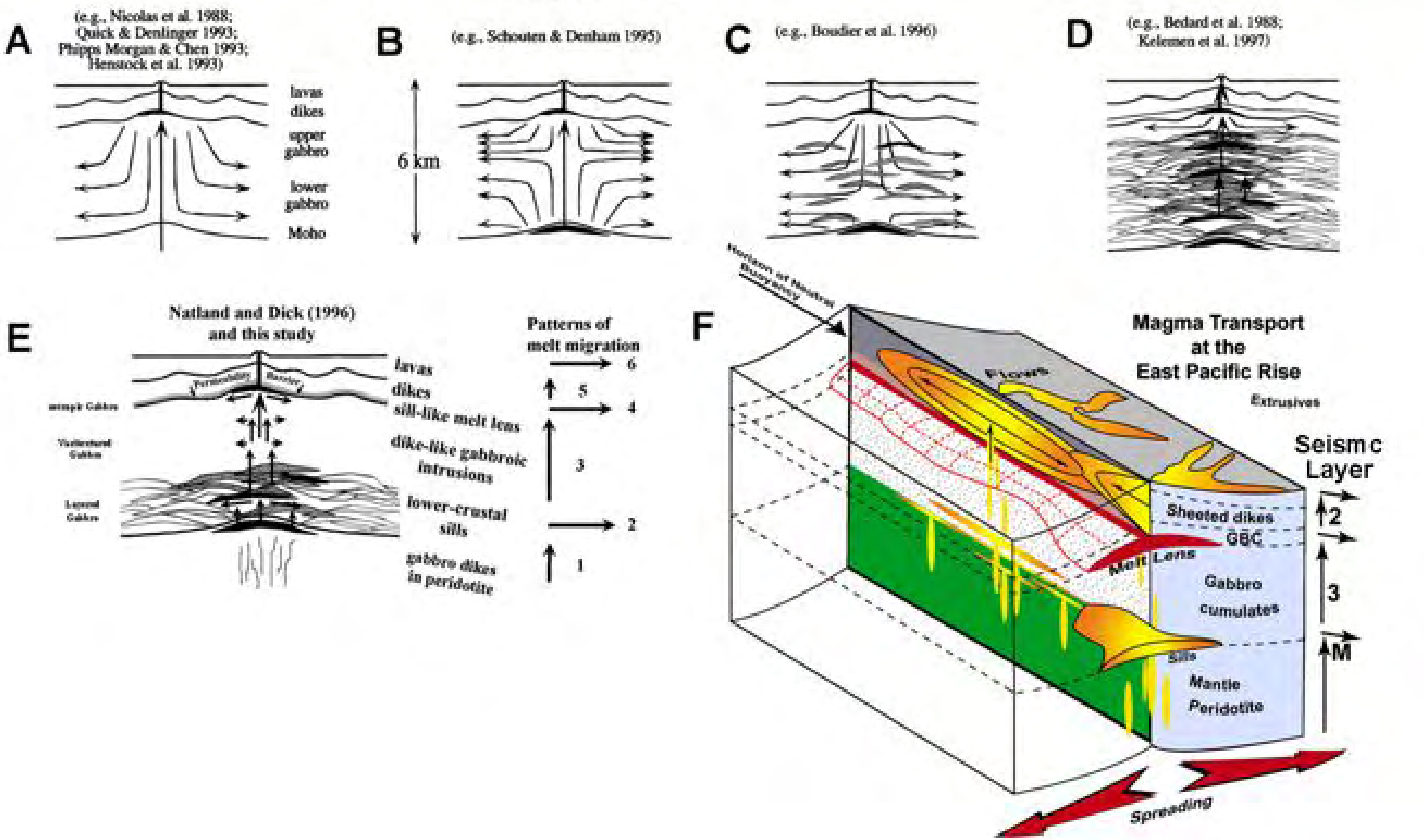
Estimation of the % of interstitial melt (residual melt porosity) in gabbro cumulates from Hess Deep, plotted versus Depth in the composite section, based on the "excess-Zr" procedure of Natland et al (1991). Blue dashed lines divide the composite section into four parts for the purpose of computing averages shown as blue triangles. Gabbros with <7& RMP are termed adcumulates in comtemporary cumulate theory, and represent very efficient expulsion of intercumulus melt in compacting and deforming cumulates.



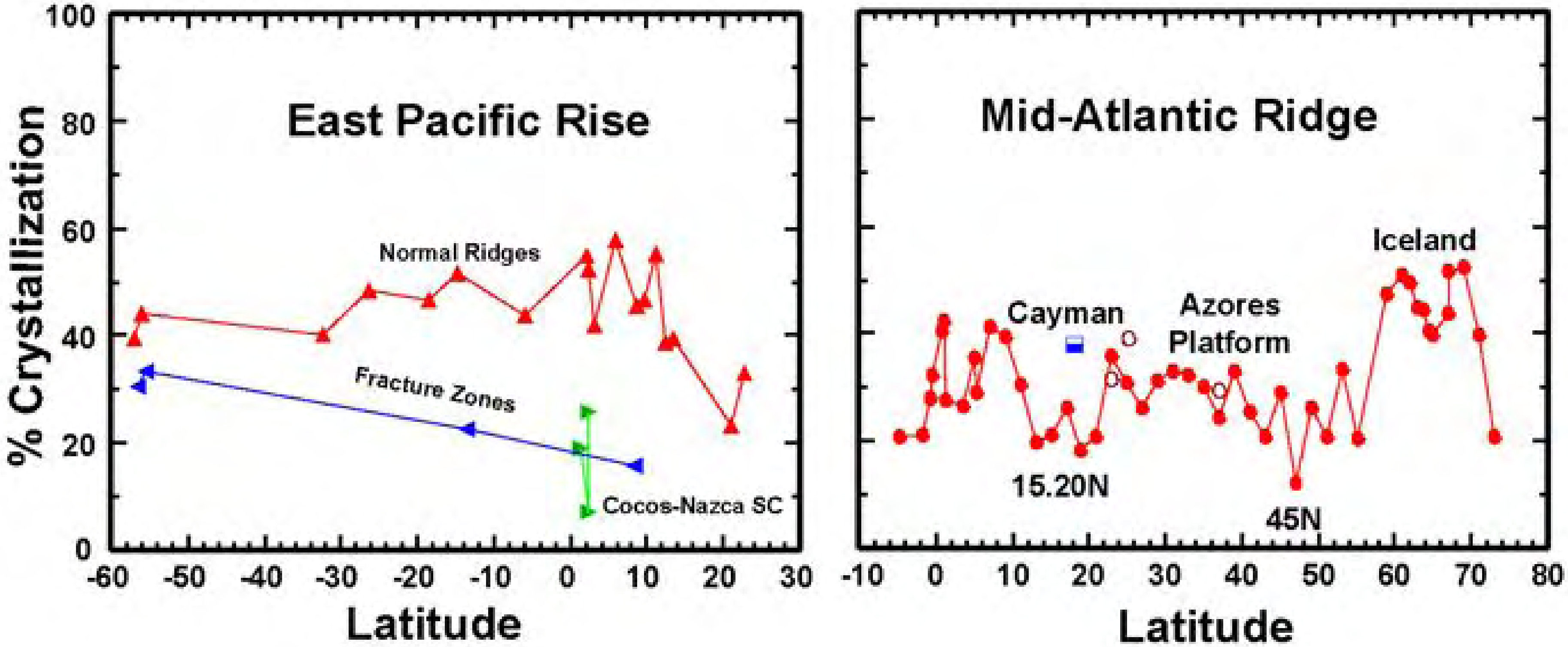
Residual melt porosity (RMP) is calculated using Zr. Zr versus MgNo for EPR basalts is well known, thus an estimate of Zr in liquids from which gabbros crystallized can be estimated using gabbro Mg# and Fe-Mg partitioning, assuming gabbro Mg# is that of its clinopyroxene. The amount of Zr not in gabbro cpx, called "excess Zr", is taken to be that in trapped liquid. This, divided by Zr in the presumed equilibrium liquid, multiplied by 100, gives RMP.

Possible cross-sections showing patterns of melt flow in compacting and crystallizing gabbros of a fast-spreading ridge, mainly from Peter Kelemen, with citations to idea progenitors given in each sub-figure. A is the "gabbro glacier" model, D is the sill model, B and C are intermediate combinations of the two. E summarizes relationships based on magmatic structures at Hess Deep. Most of the gabbroic layer crystallizes from dike-like intrusions (vertical arrows 1, 3, and 5,to right of E), except where melt appears to move laterally and forms sill-like bodies (2 and 4) or erupts onto the seafloor (g). F is a cutaway view giving a three-dimensional perspective of E, and in relation to seismic structure (Seismic Layers 2, 3 and mantle (M)

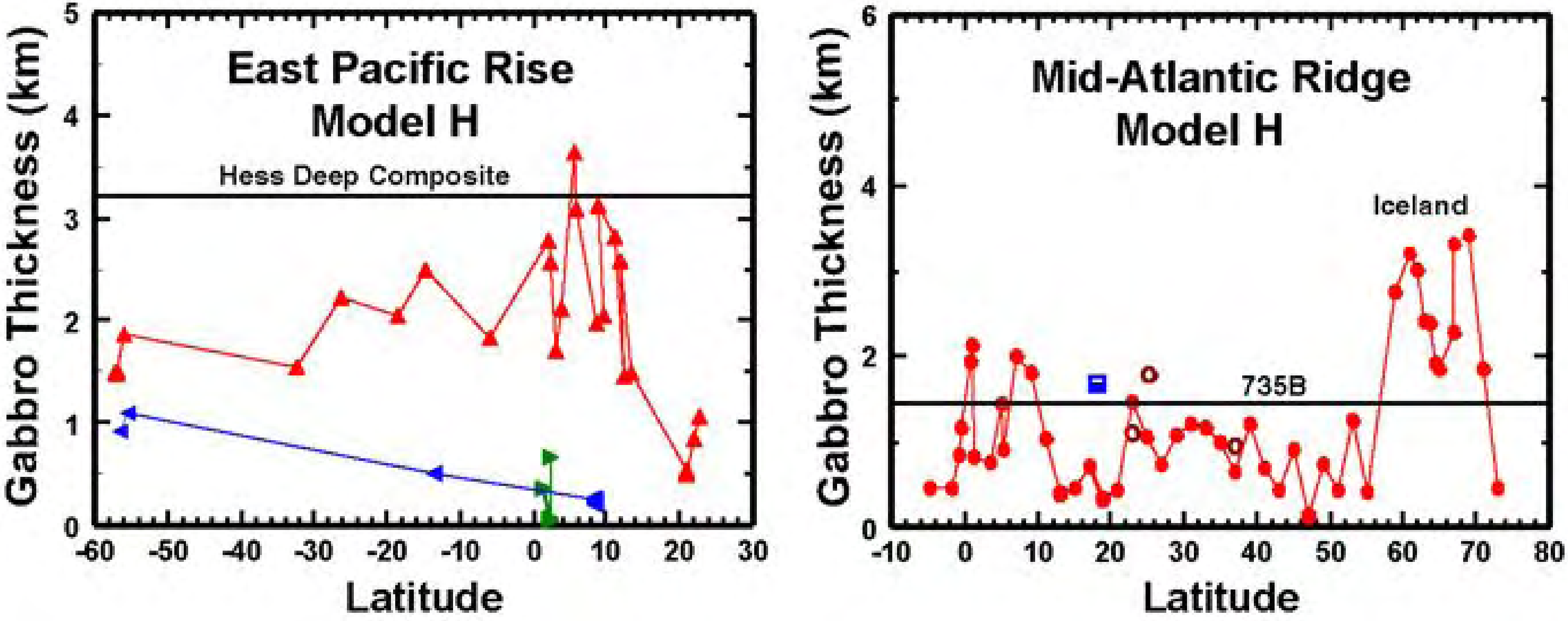
Figure 15



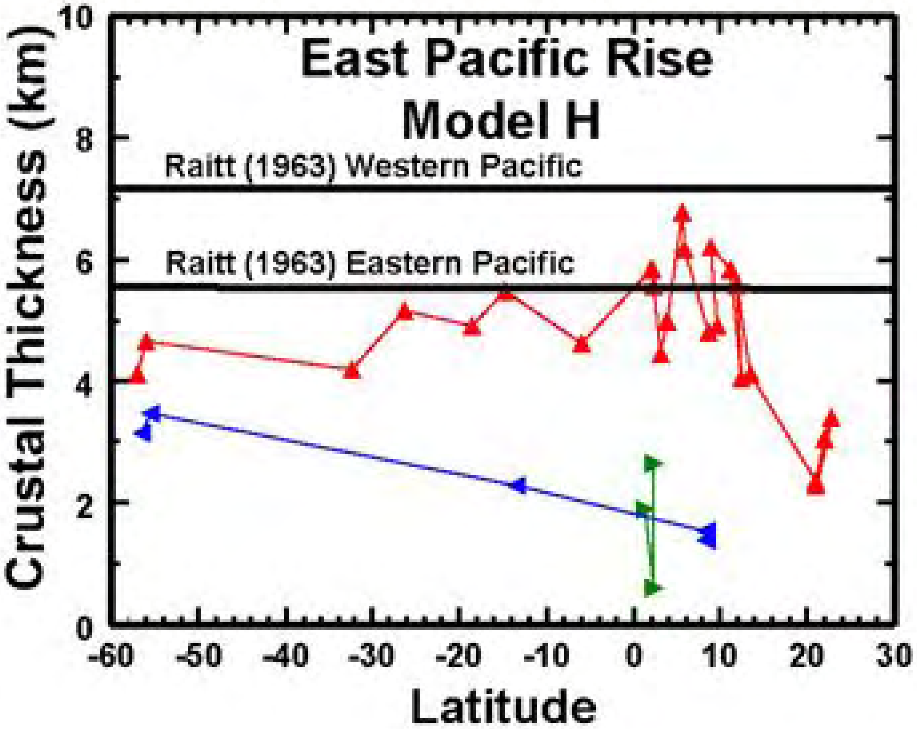
Percentages of crystallization of average basalt compositions in bins of latitude = 5 degrees for the East Pacific Rise and Mid-Atlantic Ridge. Data are taken from PetDB. The computation is based on crystallization percentages from laboratory experiments on MORB, and relates basalt MgNo to percentage of crystallization. Except for Iceland, percentages of crystallization are lower along the Mid-Atlantic Ridge than along the East Pacific Rise. Low percentages of crystallization also characterize basalts from small intra-transform volcanoes in fracture zones along the East Pacific Rise, and the tip of the Cocos-Nazca spreading center where it propagates into Hess Deep. The percentages of crystallization indicate approximately the amount of gabbro-cumulates necessary to produce the average basalt of each 5-degree bin.

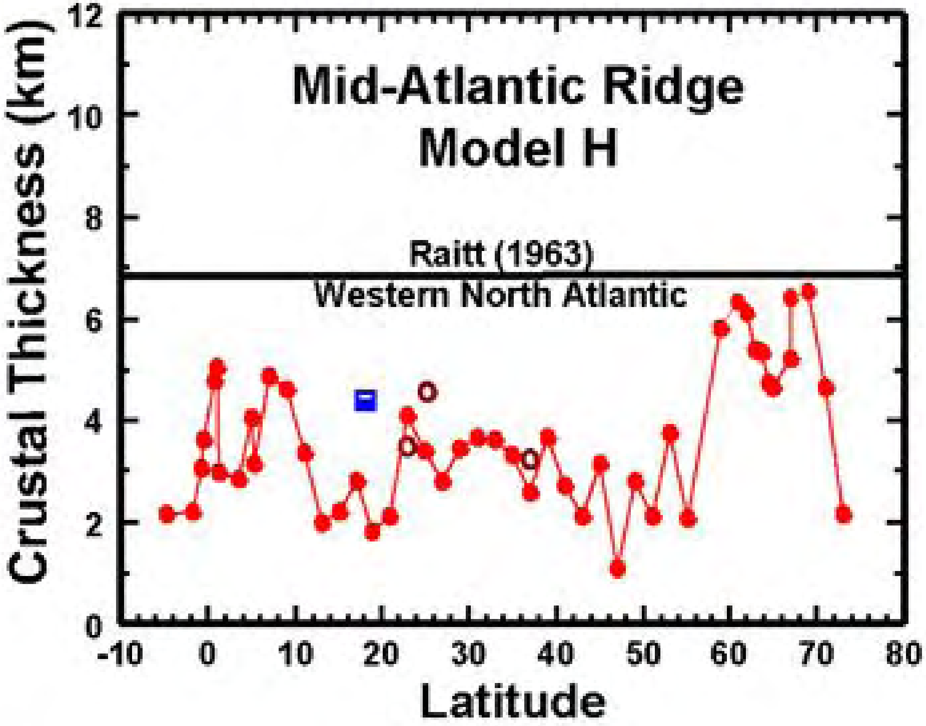


Models of minimum gabbro cumulate thickness for the East Pacific Rise (left) and Mid-Atlantic Ridge (right) based on a nominal thickness of basalts and dikes of 1.5 km, and using estimates of percentages of crystalliztion from the previous figure. The composite thickness of sections of gabbro exposed at Hess Deep is shown in the left figure for comparison. The composite thickness at Hess Deep is slightly thicker than that estimated from crystallization percentages (at about 2N Latitude), but generally at least somewhat thicker than most estimates from crystallization percentages. Estimated gabbro thicknesses for the Mid-Atlantic Ridge are much less than along the East Pacific Rise. Cored sections obtained to date of about 1500 m of gabbro (e.g., at ODP 735B), are similar to estimated thicknesses along the MAR except for Iceland. There may be significant local variability in gabbro thicknesses beneath segments at slowly spreading ridges, so that it is difficult to know whether the cored sections are representative of average thickness estimates shown here.



Adding nominal 1.5 km of dikes and pillows to estimated gabbro thicknesses in the previous figures gives an estimated crustal thickness based on petrology and the observation that Layer 2 seismic thickness does not vary greatly (from Mutter and Mutter, 1995). Here, estimated thickness of crust are compared with seismic-refraction estimates of depths to Moho from the work of Russell Raitt. Most of the Mid-Atlantic Ridge (except Iceland) and portions of the East Pacific Rise fall short of the seismic evidence. Is this because hydrothermal systems penetrate through gabbros, reach peridotites, and form serpentinite? Hess's query of 1960-1962 is alive and well!





The general subsidence of the ocean floor, with depth being related to the square-root of the crustal age, is explained by thermal contraction of the lithosphere, reaching a maximum of about 5% in crust of Mesozoic age. Contraction has to be lateral as well as vertical, suggesting that tensional fissures should form in the crust and allow water to penetrate into it, perhaps even into the mantle.

Echo-sounding has Revealed a general Pattern of deepening Of the ocean floor Away from spreading Ridges (Figure provided By the late Roger L. Larson)

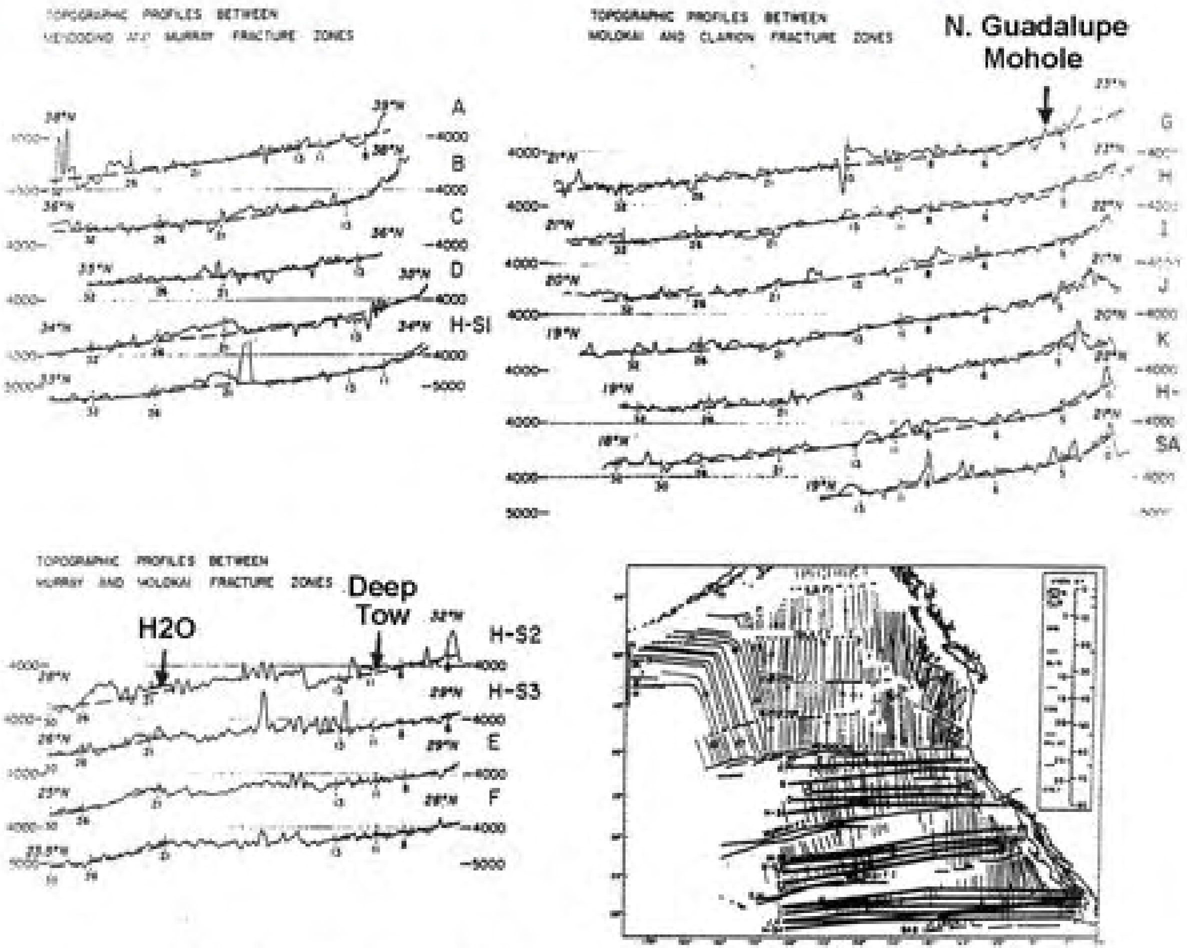
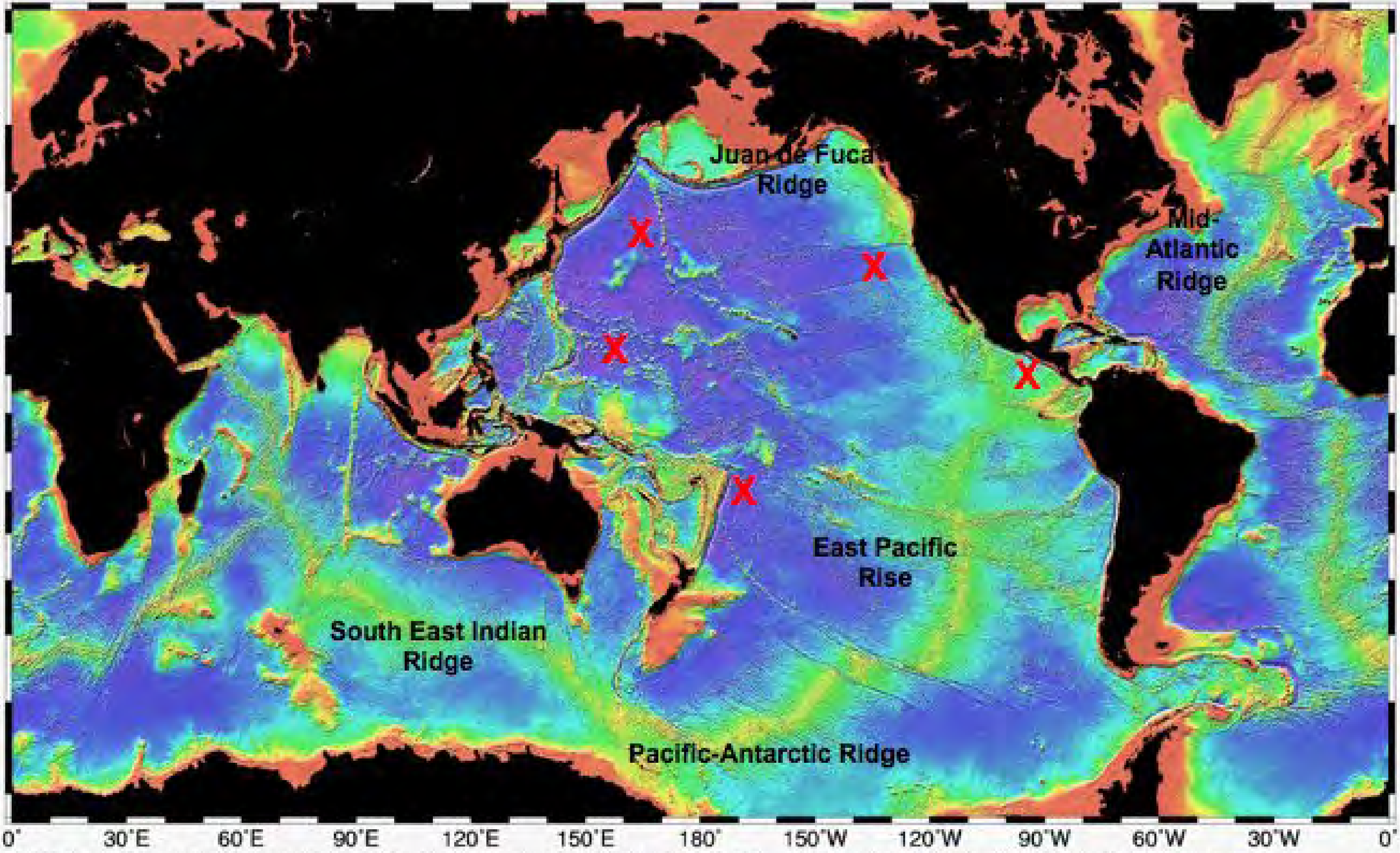


Fig. 1. Sixteen topographic profiles parallel to the fracture zones in the North Pacific. The tracks are shown on the magnetic anomaly chart of *Atwater and Menard* [1970]. The latitudes are shown above and the distinctive magnetic anomalies below the topographic profiles. The dashed lines represent the smoothed curves drawn on the profiles for data analysis. Corrected meters have been used for all topographic profiles presented in this paper.

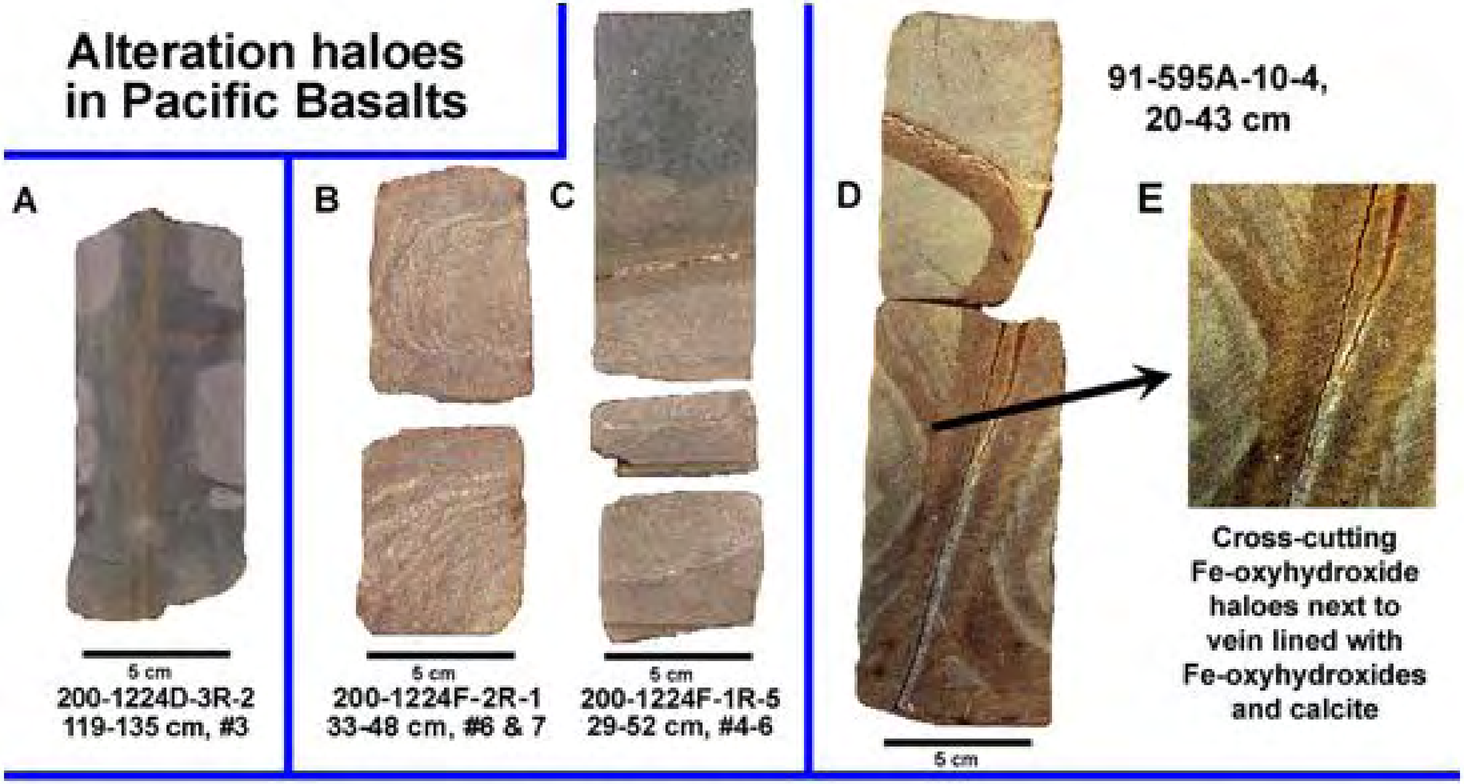
Drill sites that give information about Alteration in Basalts and Dikes Of Fast-spread Crust in the Pacific



Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996

We don't have much information about penetration of seawater into older fast-spread crust. Most of it is based on short drilled sections into the upper 50-300 m of basalt. Nevertheless, striking patterns of alteration are evident in many of these basalts, patterns not evident at all in "zero-age" basalt dredged from the axis of the East Pacific Rise. How far do such patterns extend into crust of Mesozoic age in the Pacific?

Alteration haloes in Pacific Basalts



A: 200-1224D-3R-2 119-135 cm, #3

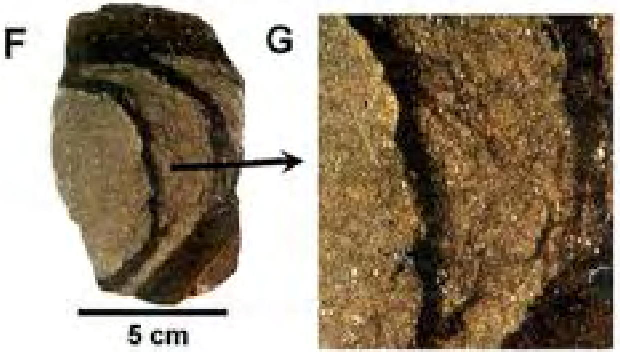
B: 200-1224F-2R-1 33-48 cm, #6 & 7

C: 200-1224F-1R-5 29-52 cm, #4-6

D, E: 91-595A-10-4, 20-43 cm

Cross-cutting Fe-oxyhydroxide haloes next to vein lined with Fe-oxyhydroxides and calcite

91-595A-10-1, 1-10 cm



Detail of penetration of Fe-oxyhydroxides along microfractures

Conclusions

- What we have learned so far from abyssal gabbros suggests that Seismic Layer 3 is thicker than the “gabbroic layer”, especially at slowly-spreading ridges.
- Seismic Layer 3 at older fast-spreading ridges may be 1-2 km thicker than the gabbroic layer at younger fast-spreading ridges.
- One possibility is that an “alteration front” penetrates downward through the gabbros and serpentinizes the uppermost mantle.
- This is suggested by existing drill sites in the Pacific, which indicate that alteration continues in uppermost basalts for many millions of years.
- Alternatively or in addition, significant proportions of the gabbroic layer crystallize *in situ* and have no corresponding extrusives or dikes.
- Either way, the only way to find out is to drill entire crustal sections of older crust where Moho is clearly established seismically, both to determine the extent of alteration at depth, and to obtain the bulk composition of the entire crust.
- This will also establish what returns to the mantle at subduction zones.

Past and Future Drilling in Tectonic Windows

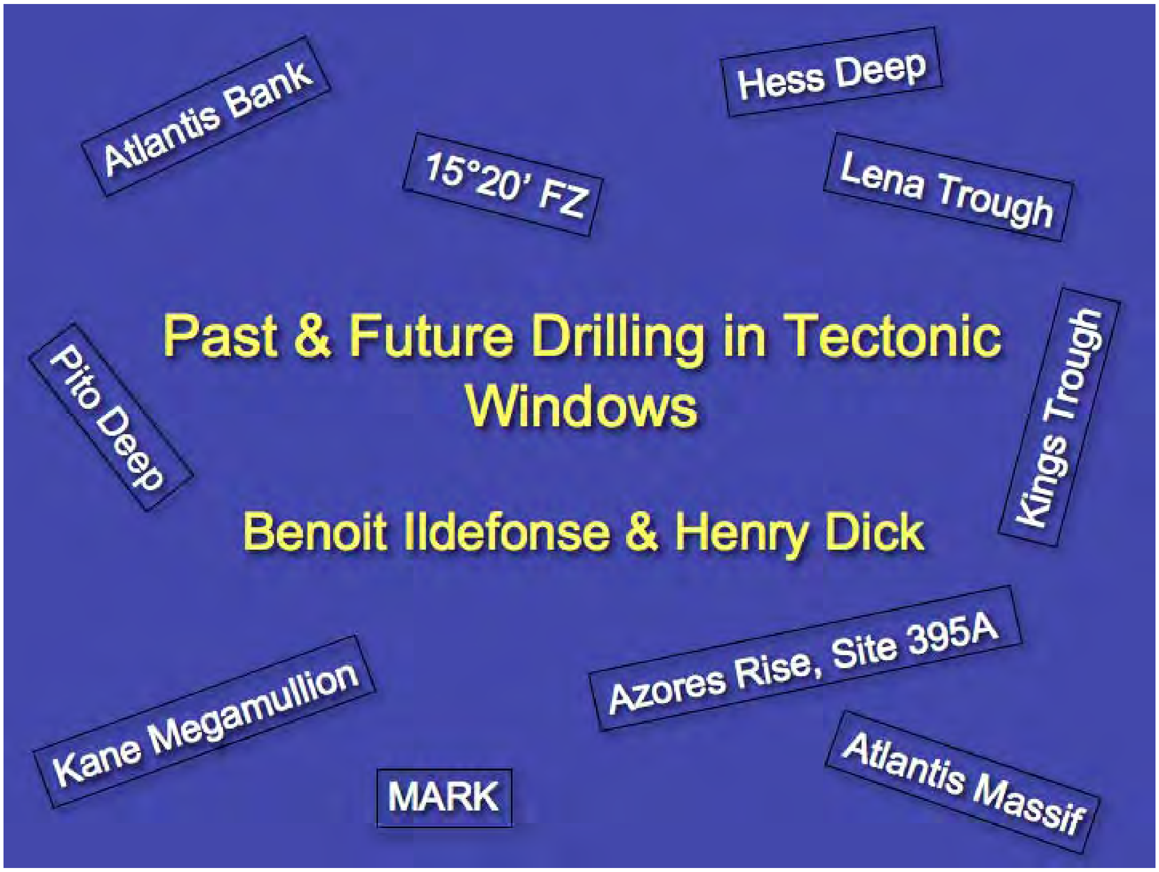
Henry J.B. Dick and Benoît Ildefonse

Past & Future Drilling in Tectonic Windows

Henry J.B. Dick & Benoit Ildefonse

Modified from a presentation of the same title at the Moho Workshop

Nov. 28th 2006



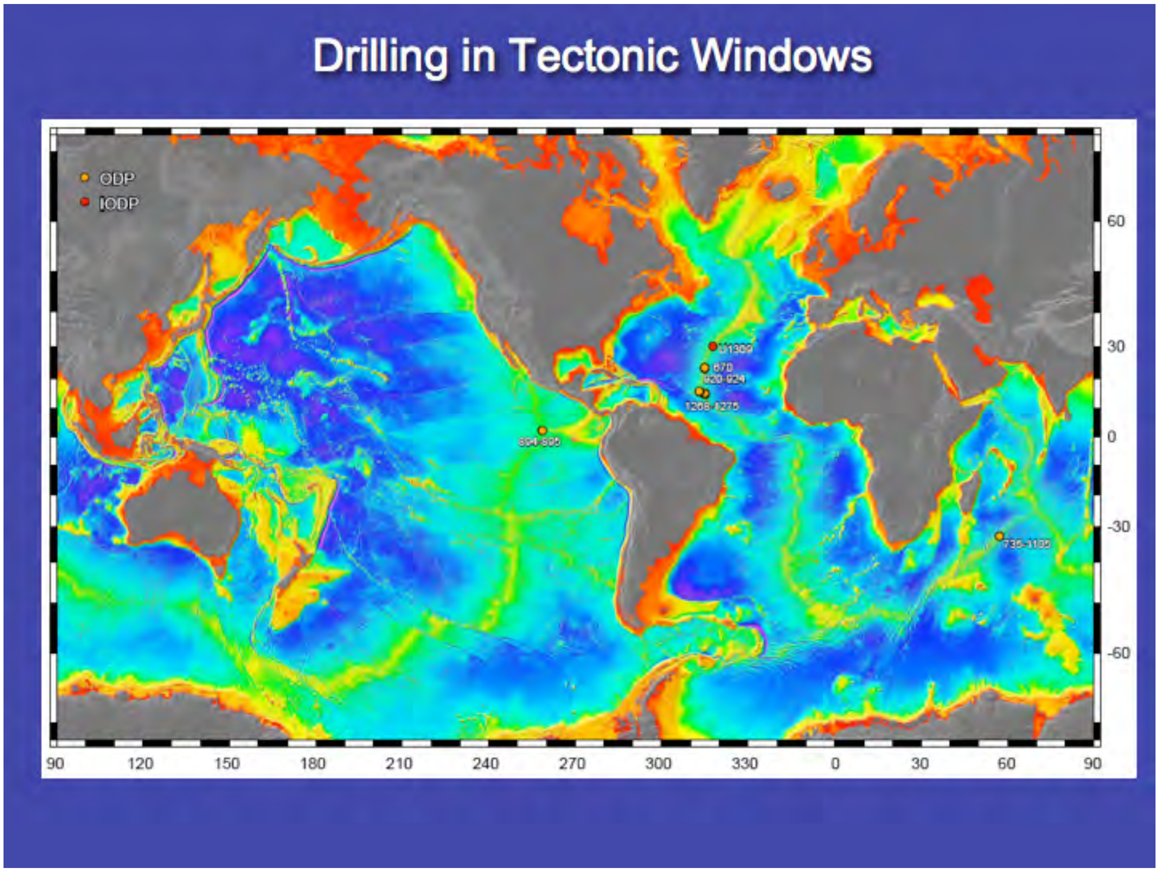
Past & Future Drilling in Tectonic Windows

Benoit Ildefonse & Henry Dick

Slide 1

At the time of the Penrose Ophiolite Conference in 1971, there was a consensus that the ocean crust was relatively uniform in thickness, with a simple layered structure of lavas, sheeted dikes, and gabbros overlying mantle peridotite tectonite. This consensus no longer exists, as detailed exploration and ocean drilling have revealed an ocean crust whose architecture varies with spreading rate, ridge geometry, and proximity to mantle hotspots. While at fast spreading ridges, crustal architecture is thought to closely resemble the Penrose model, with a simple relatively uniform layered structure – even there it is now know from drilling at Site 1256D, that sheeted dike layer thins substantially with increasing spreading rate. At slow spreading ridges, crustal architecture evidently varies dramatically on scales ranging from the length of an axial volcanic segment, to hundreds of meters. Given that after 30 years of ocean drilling, earth scientists have only just now penetrated to gabbroic layer 3 in the Pacific, it is clear that drilling intact sections through the ocean crust, if achieved at all, will only be done in a few places. A single penetration to Moho in the Pacific alone, will require substantial resources and planning. Given the highly variable nature of the ocean crust, and the possibility that seismic Moho may represent several different things (a boundary between upper mantle peridotite tectonite; a broader zone of interlayered mafic intrusives and peridotite, or an alteration front), it is clear that defining the nature of Moho and the architecture of the ocean crust cannot be done simply by drilling one or two total penetrations of intact ocean crust.

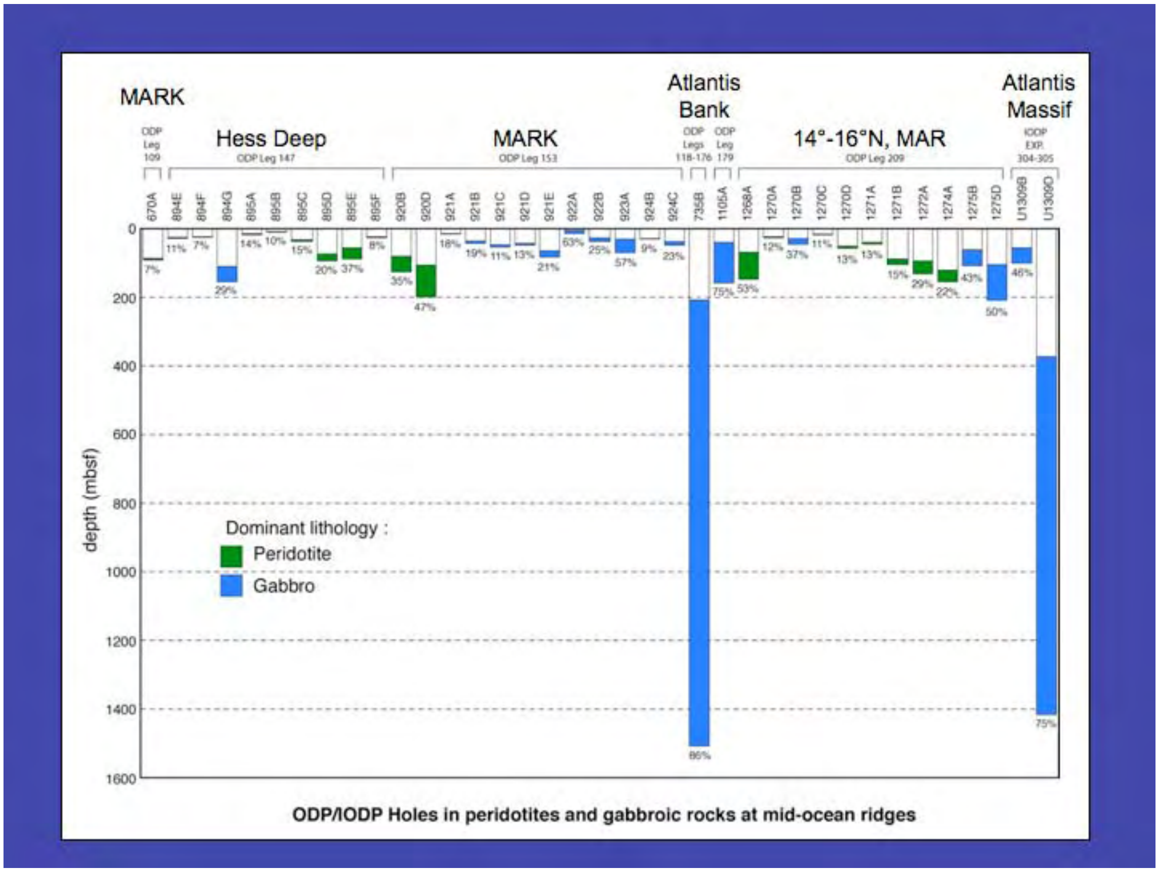
Tectonic windows, where extensional tectonics at propagating rift tips or detachment faulting at slow and ultraslow spreading ridges expose deep sections of the lower crust and mantle, however, provide the opportunity to explore the lower ocean crust in three dimensions at all spreading rates without drilling many kilometers. In particular, assessing the nature of Moho in different magmatic environments will require this.



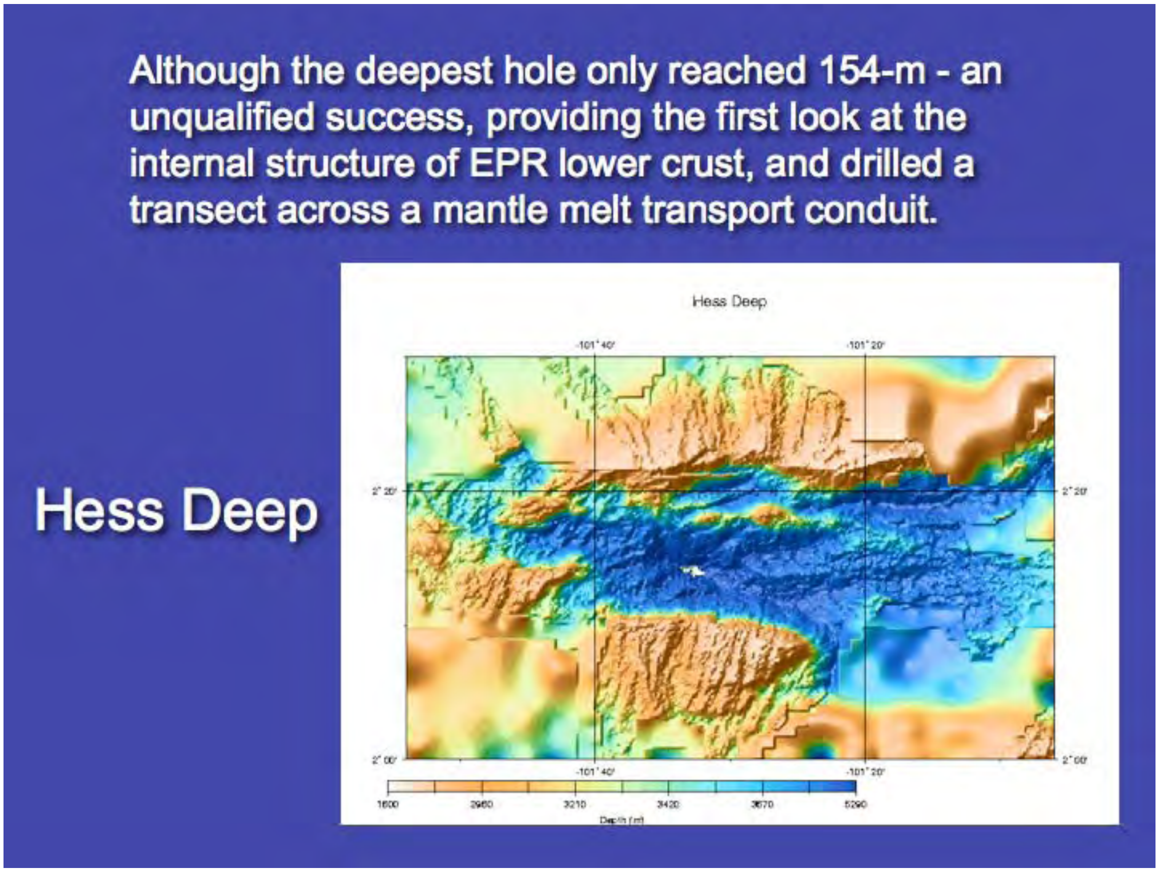
Drilling in Tectonic Windows

Slide 1

To date relatively few holes have been drilled in tectonic windows, as illustrated in Slides 1&2. Such drilling really began with Leg 109, which opportunistically drilled a nearly 100-m section of mantle peridotite on the eastern rift valley wall of the Mid-Atlantic Ridge south of the Kane Fracture Zone. The first major attempt at using tectonic windows to drill the lower crust and mantle, however, occurred on a wave cut platform at Atlantis Bank on the ultraslow spreading SW Indian Ridge, where Hole 735B, initiated on ODP Leg 118, penetrated 1508-m into gabbroic layer 3 before the drill string broke off in a storm and blocked the Hole. This success was followed, with mixed results by drilling at Hess Deep, where amagmatic rifting ahead of the Cocos-Nazca ridge exposed tectonic blocks of lower crust and mantle formed at the East Pacific Rise. In this highly tectonized environment, however, drilling conditions proved very difficult, and only relatively short sections of lower crust gabbro and mantle peridotite were obtained by offset drilling. A similar result was achieved during drilling during ODP 153 on an active detachment fault on the rift valley wall near the eastern inside-corner high of the Kane Fracture Zone (MARK area). At the end of ODP, Leg 209 drilled a series of successful offset drill holes north and south of the 15°20’ Fracture Zone on the Mid-Atlantic Ridge, where the ocean crust appears to be anomalously thin, to explore the architecture of the upper mantle beneath an ocean ridge. Leg 209 recovered a series of mantle peridotite sections heavily intruded by small gabbro plugs that were evidently emplaced beneath a discontinuous thin basaltic carapace. More recently, enormous success was obtained at Hole U1309D at the eastern intersection of the Atlantis Fracture Zone and the Mid-Atlantic Ridge, which penetrated 1415-m it a complex series of oceanic gabbros, where mantle peridotite was expected from the site survey work. The results of this drilling greatly modified our concepts of how the lower ocean crust formed at slow and ultraslow spreading ocean ridges, and has revealed strikingly different crustal architecture at fast, slow, and ultraslow spreading ridges.



ODP/IODP Holes in peridotites and gabbroic rocks at mid-ocean ridges

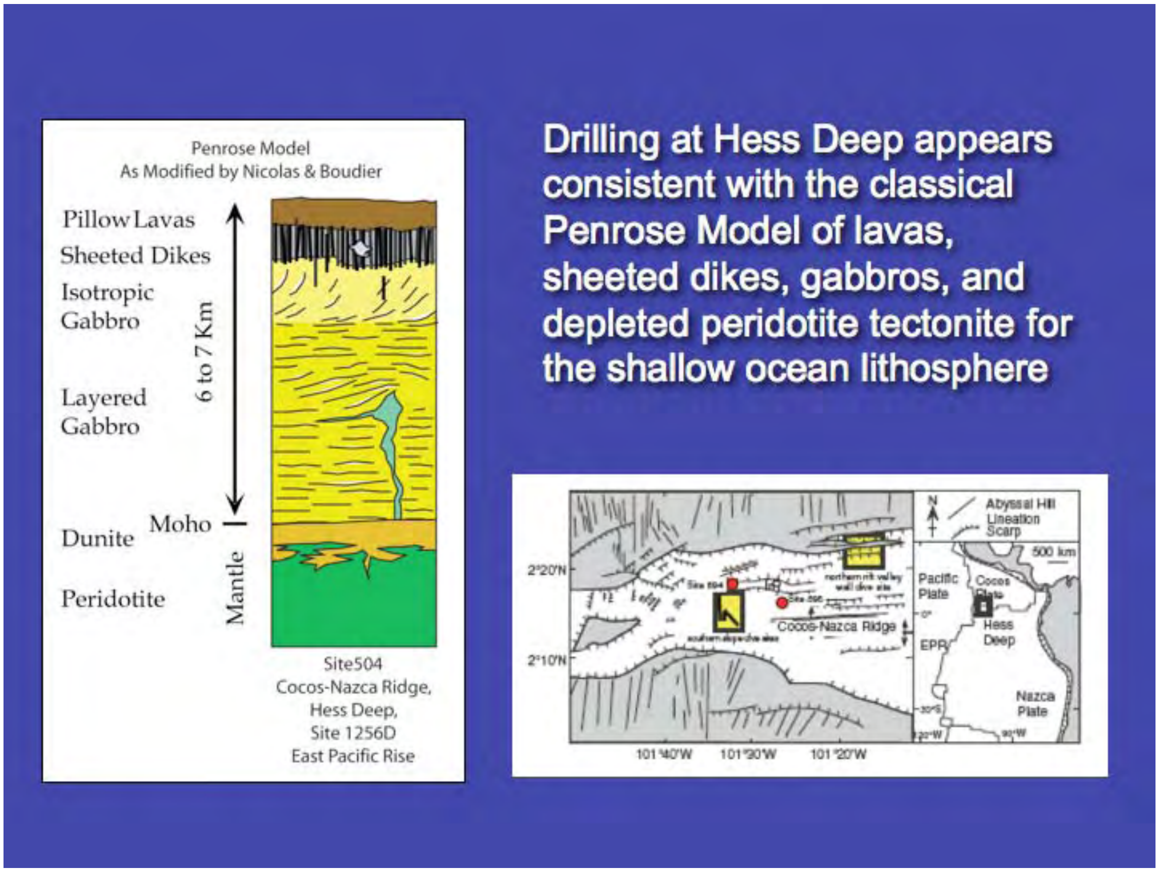


Although the deepest hole only reached 154-m - an unqualified success, providing the first look at the internal structure of EPR lower crust, and drilled a transect across a mantle melt transport conduit.

Hess Deep

Slide 3

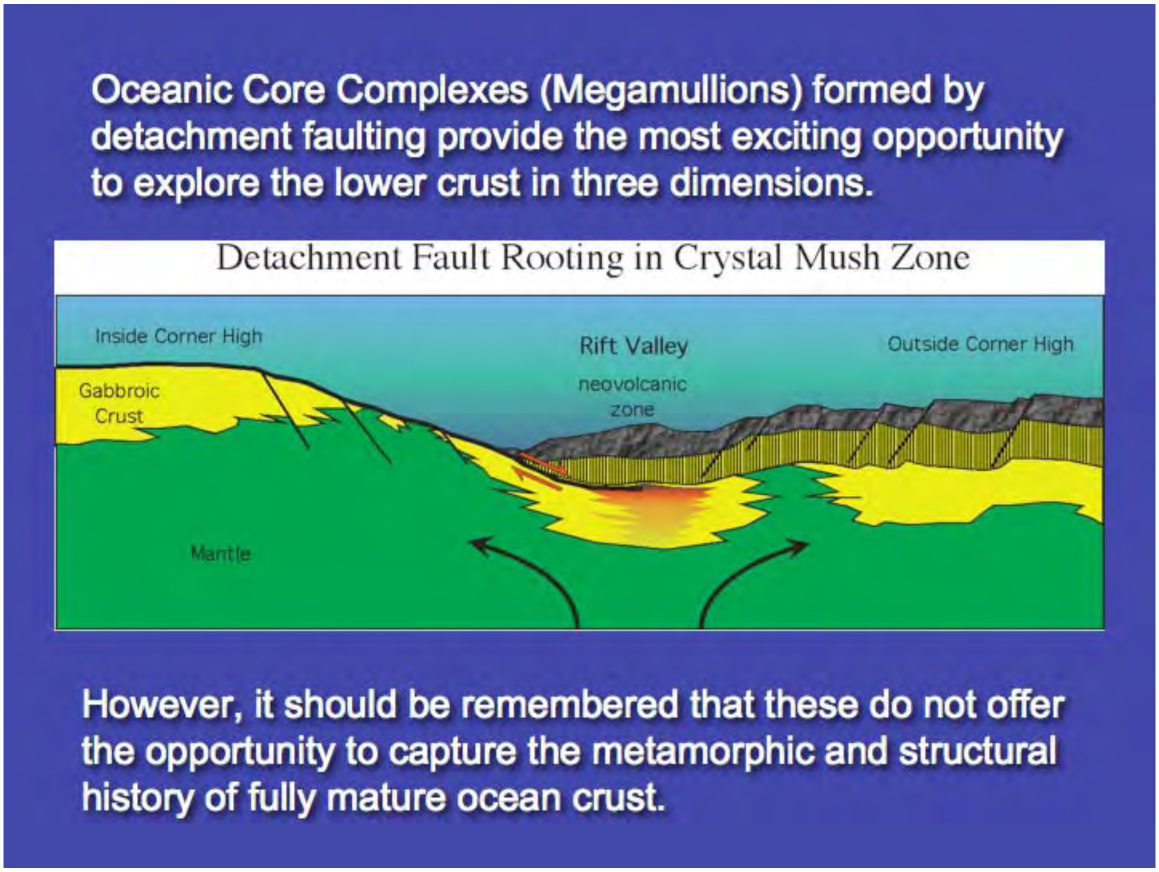
Drilling at Hess Deep on ODP Leg 147 occurred in a foundered tectonic block exposing mantle peridotite tectonite and lower crustal gabbros at the tip of the Cocos-Nazca Rift (Slides 3 &4). Although the deepest penetration there reached only 154-m in a section of fine to medium grained gabbros at Site 894G, these rocks were consistent with the remains of the postulated melt lens beneath the East Pacific Rise, and appear to confirm that the seismic layer 2-3 boundary corresponds to a relatively sharp sheeted dike-gabbro transition. At the same time, a suite of holes drilled at Site 895 up a mantle section on the tectonic block crossed a mantle melt transport conduit that cut residual peridotite tectonites. These conduits consisting of dunite, showed that melt delivery is locally focused through the shallow mantle at fast spreading ridges, and that mid-ocean ridge basalt aggregates from different melt fractions within the mantle.



Drilling at Hess Deep appears consistent with the classical Penrose Model of lavas, sheeted dikes, gabbros, and depleted peridotite tectonite for the shallow ocean lithosphere

Slide 4

Leg 147 demonstrated the utility of a series of short offset holes in tectonic windows to obtain direct information on the lateral variability of the crust and mantle not obtainable by a single deep hole. Moreover, the results are consistent with the widely accepted view that the Penrose model describes well crustal architecture formed at fast spreading ridges.



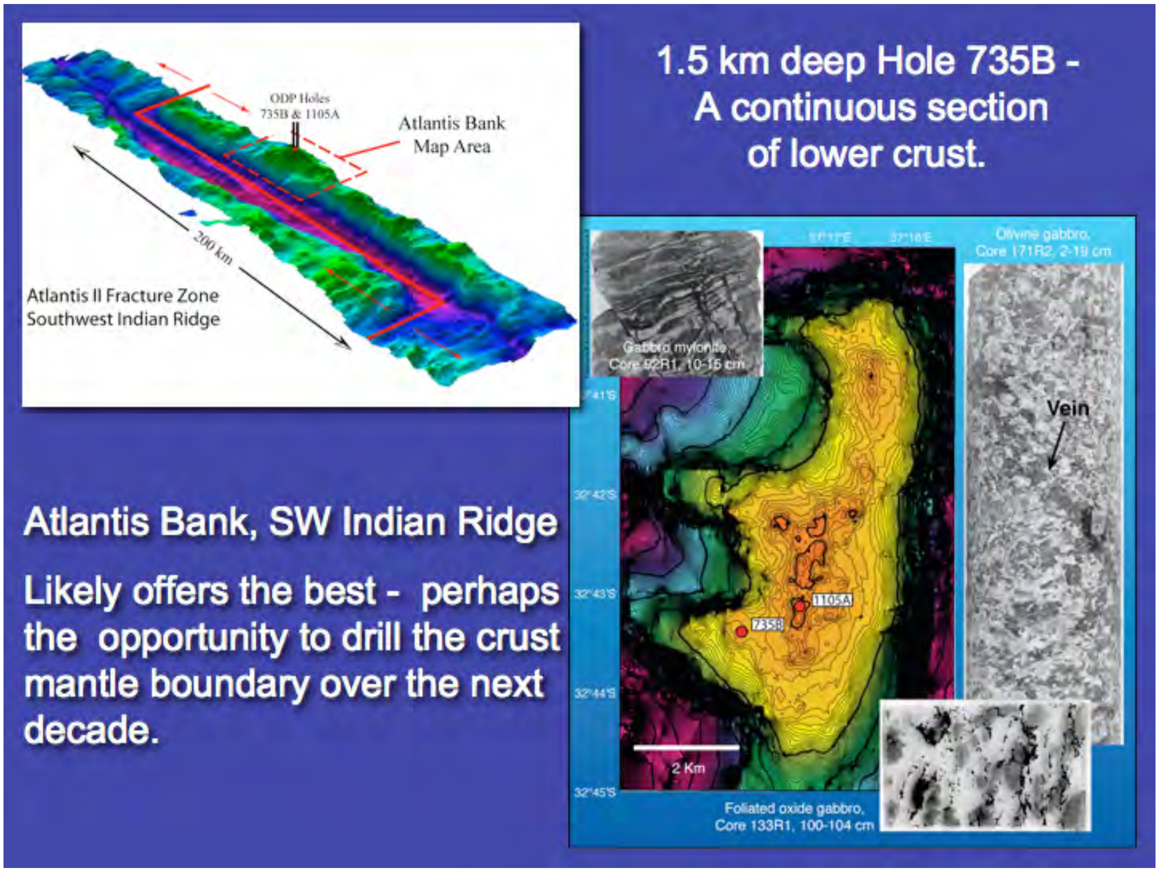
Oceanic Core Complexes (Megamullions) formed by detachment faulting provide the most exciting opportunity to explore the lower crust in three dimensions.

Detachment Fault Rooting in Crystal Mush Zone

However, it should be remembered that these do not offer the opportunity to capture the metamorphic and structural history of fully mature ocean crust.

Slide 5

Deep drilling in tectonic windows has occurred at two locations: the Atlantis Massif at the inside-corner high of the Atlantis Fracture Zone on the Mid-Atlantic Ridge and at Atlantis Bank, a ~11 m.y. old wave cut platform at the crest of the eastern wall of the Atlantis II Fracture Zone on the SW Indian Ridge. At both locations, the gabbroic rocks were exposed by detachment faulting on the rift valley wall that appears to have rooted into or passed through gabbroic crust near the dike-gabbro transition (Slide 5). At both sites, long sections of gabbroic rock were recovered revealing a complex history of intrusion, re-intrusion and deformation during accretion. In this light, it must be noted that such tectonic window cannot be unaffected by the enormous tectonic forces that unroofed the complexes from beneath lavas and dikes and exposed them to the sea floor. Moreover, as hydrothermal circulation and alteration of the ocean crust, in the absence of such faulting, proceeds at depth beneath a 1-2 km cover of highly fractured pillow lavas and sheeted dikes even after the section has passed into the rift mountains, these sections do not provide a window into the alteration of intact sections of ocean crust.



1.5 km deep Hole 735B -
A continuous section
of lower crust.

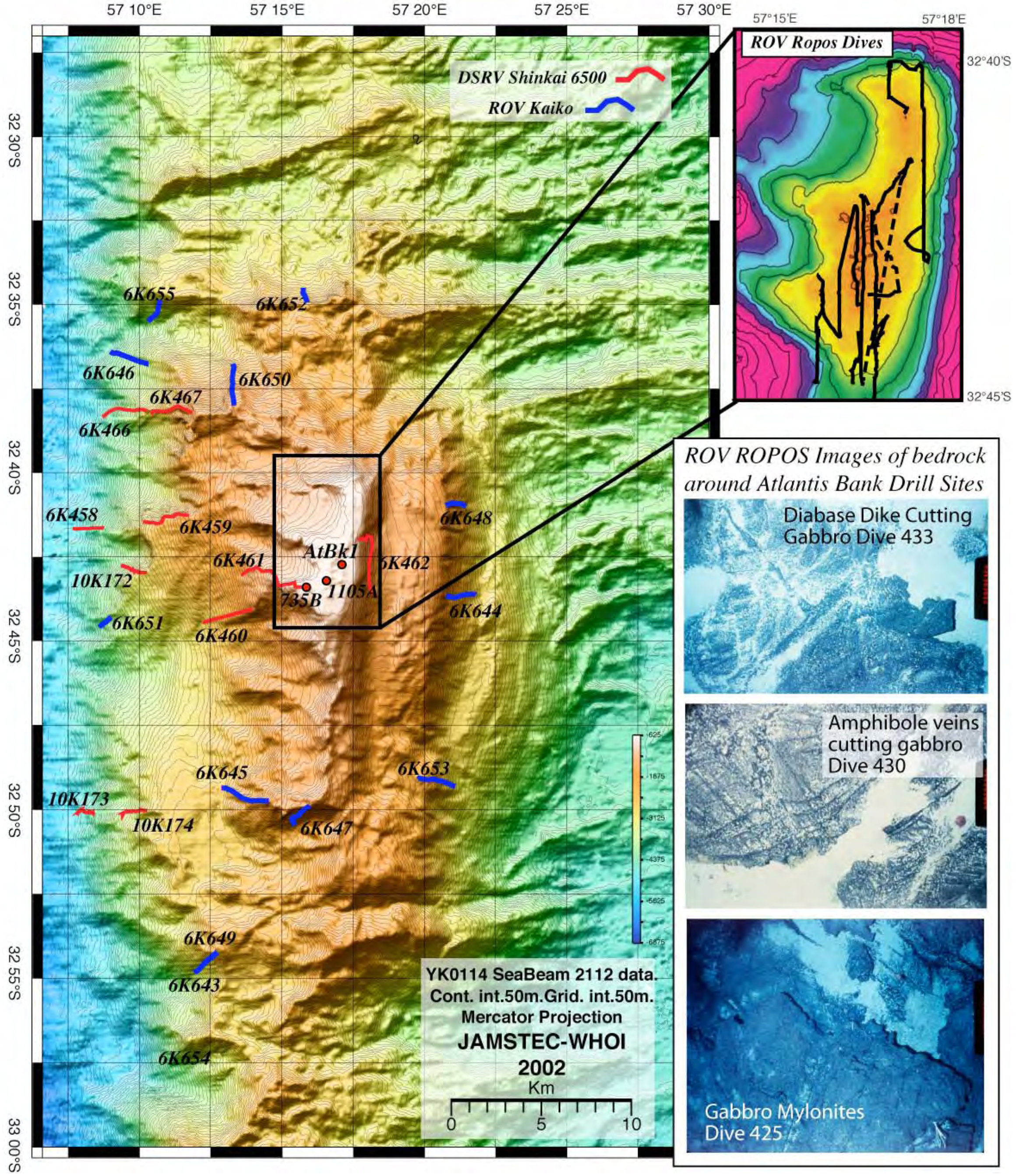
Atlantis Bank, SW Indian Ridge

Likely offers the best - perhaps the opportunity to drill the crust mantle boundary over the next decade.

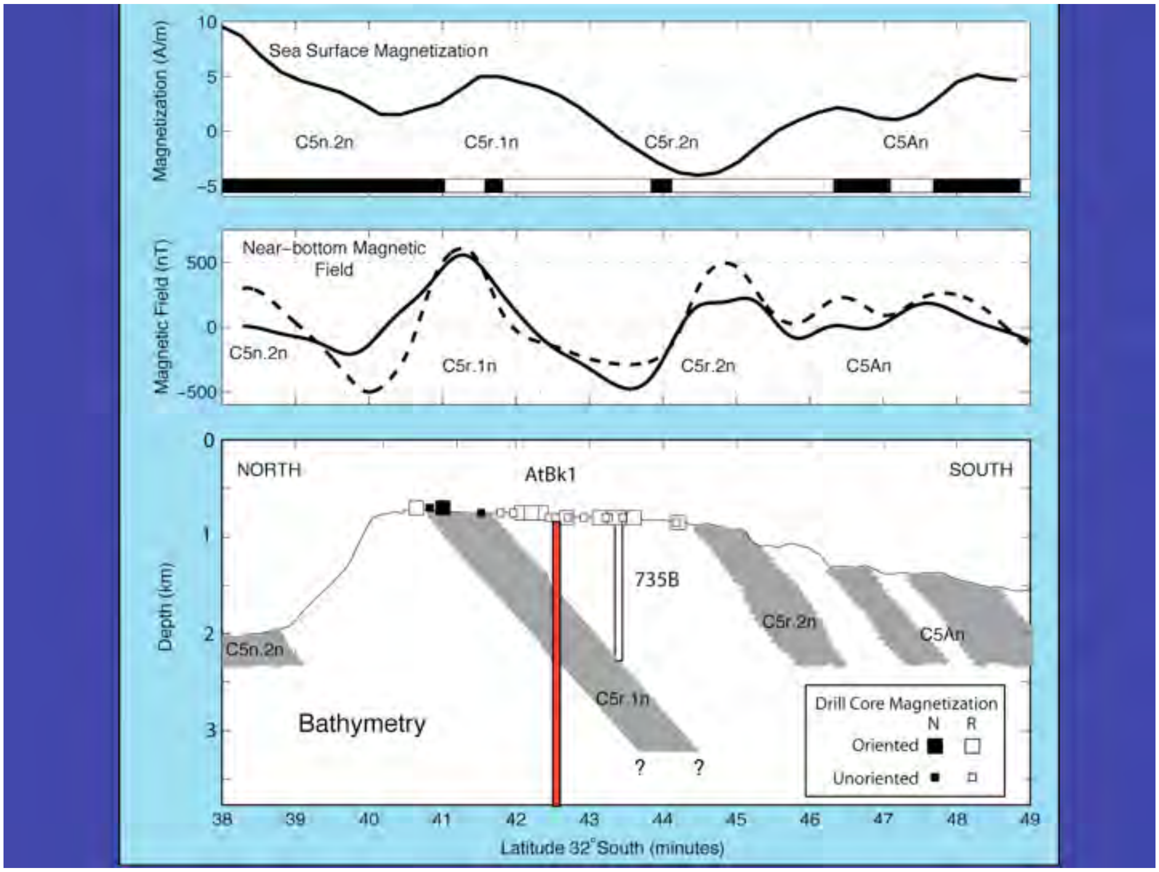
Slide 6

Nonetheless, deep drilling at Atlantis Massif and Atlantis Bank have profoundly impacted our understanding of the accretion of the lower crust at slow and ultraslow spreading ridges. Together they demonstrate the existence of a thick gabbroic layer 3 in this environment, and are consistent with a modified Penrose model for the lower ocean crust. While the lateral extent of the gabbroic crust drilled at Hole U1309D remains uncertain, with the possibility that an intrusive contact exists nearby with relatively unaltered mantle peridotite exposed to the seafloor, this is not the case at Atlantis Bank, where dredging, over-the-side diamond coring, and numerous ROV (ROPOS & Kaiko) and submersible dives (Shinkai 6500) have documented a 400 km^2 continuous gabbro massif intruding into mantle peridotites on the wall of the Atlantis II Fracture Zone. There, erosion has created a ~24 km^2 wave cut platform at 750-m water depth, locally removing fault gouge and exposing bare gabbro outcrops where the internal structure can be seen directly over a large area (Slide 6). Seismic surveys have located Moho at ~4-5 km beneath Atlantis Bank, which, with its old age, shallow depth, ease of guidebase placement, and lack of thermal problems for deep drilling, likely make it the best near-term opportunity to drill the crust-mantle transition, and likely the best place to do so at slow and ultraslow spreading magmatic crust.

Atlantis Bank SW Indian Ridge

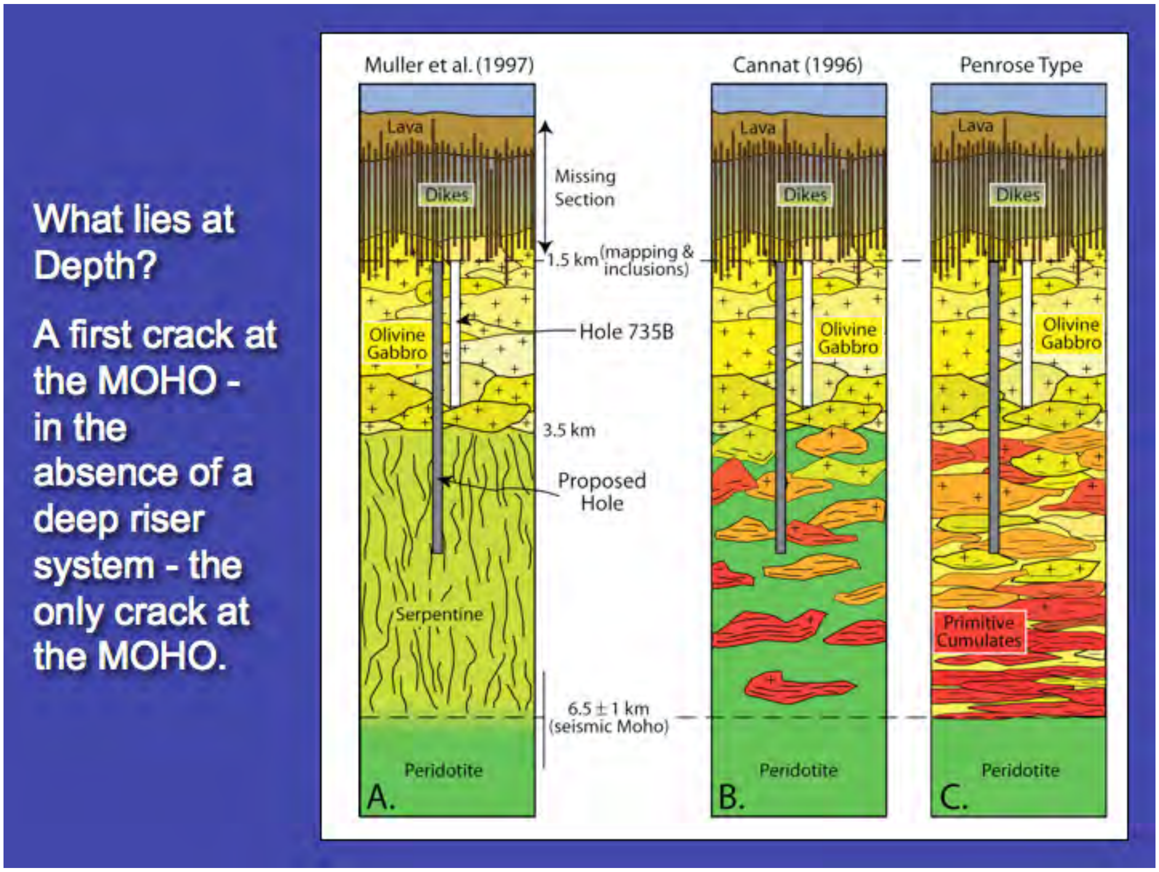


Slide 7



Slide 8

While Hole 735B is blocked, it's great depth provides the opportunity by drilling a hole nearby, to assess the continuity and lateral variability of the lower crust at a geologically meaningful scale. Thus, the Ocean Drilling Science Advisory Panels recommended moving the location for additional drilling to a new site. This also offers the opportunity to test the nature of such magnetic transitions in lower ocean crust. Atlantis Bank exposes a normal-reverse polarity transition which appears from following the magnetic stripes down the transform wall, to dip steeply to the South (Slide 8). Thus, by offsetting the new hole a sufficient distance from the transition between anomalies, a geologically meaningful section above, through, and below a magnetically reversed zone can be obtained - a possibly unique opportunity

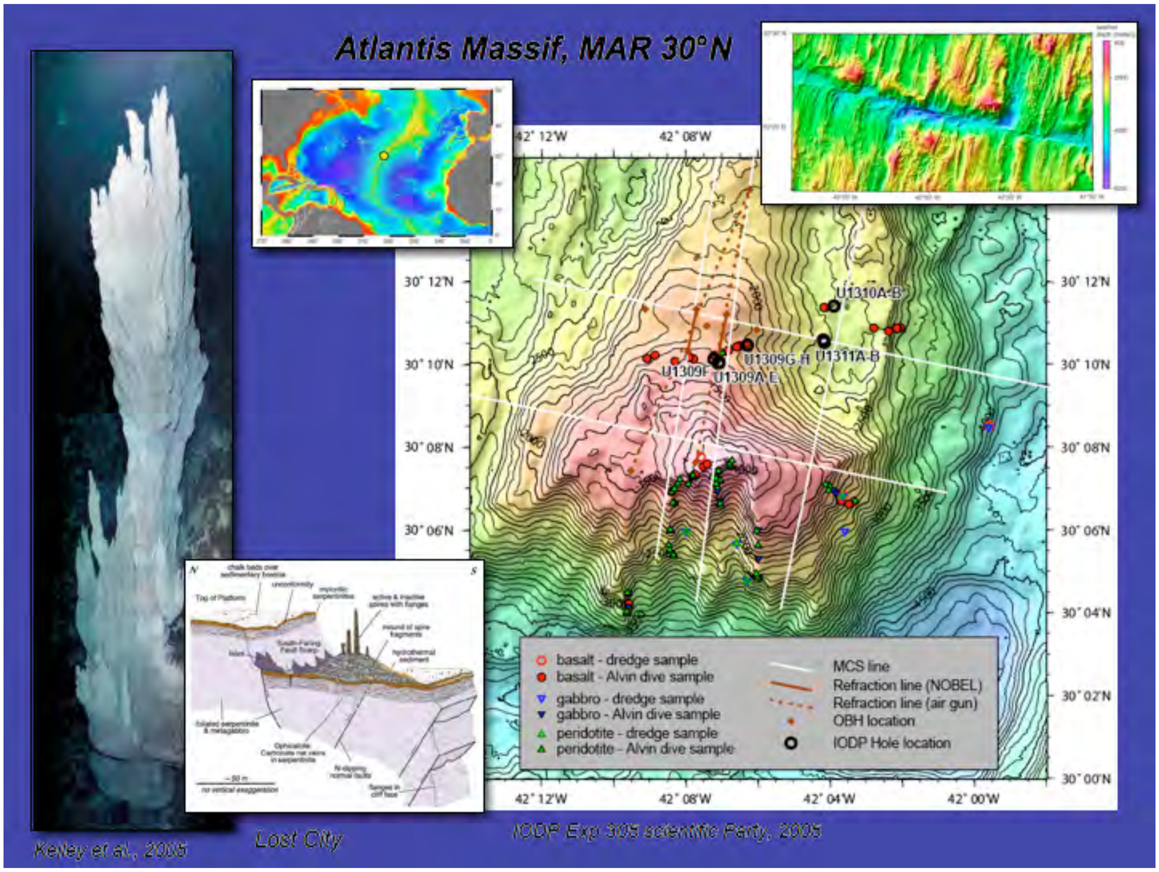


What lies at Depth?

A first crack at the MOHO - in the absence of a deep riser system - the only crack at the MOHO.

Slide 9

The ultimate goal of a deep penetration at Atlantis Bank would be to test the nature of Moho there, which has been variously proposed as an alteration front beneath a relatively thin gabbro layer, a transition of mixed mafic and ultramafic rocks, or simply the contact between a thick gabbro layer and mantle peridotite tectonites. As shown Slide 9, even a 3 km hole could go a long way towards resolving this anomaly, while at the same time determining if there is a systematic variation in the composition of the lower crust with depth.



Atlantis Massif, MAR 30°N

- ○ basalt - dredge sample
- ● basalt - Alvin dive sample
- ▽ gabbro - dredge sample
- ▼ gabbro - Alvin dive sample
- △ peridotite - dredge sample
- ▲ peridotite - Alvin dive sample
- MCS line
- Refraction line (NOBEL)
- Refraction line (air gun)
- OBH location
- ○ IODP Hole location

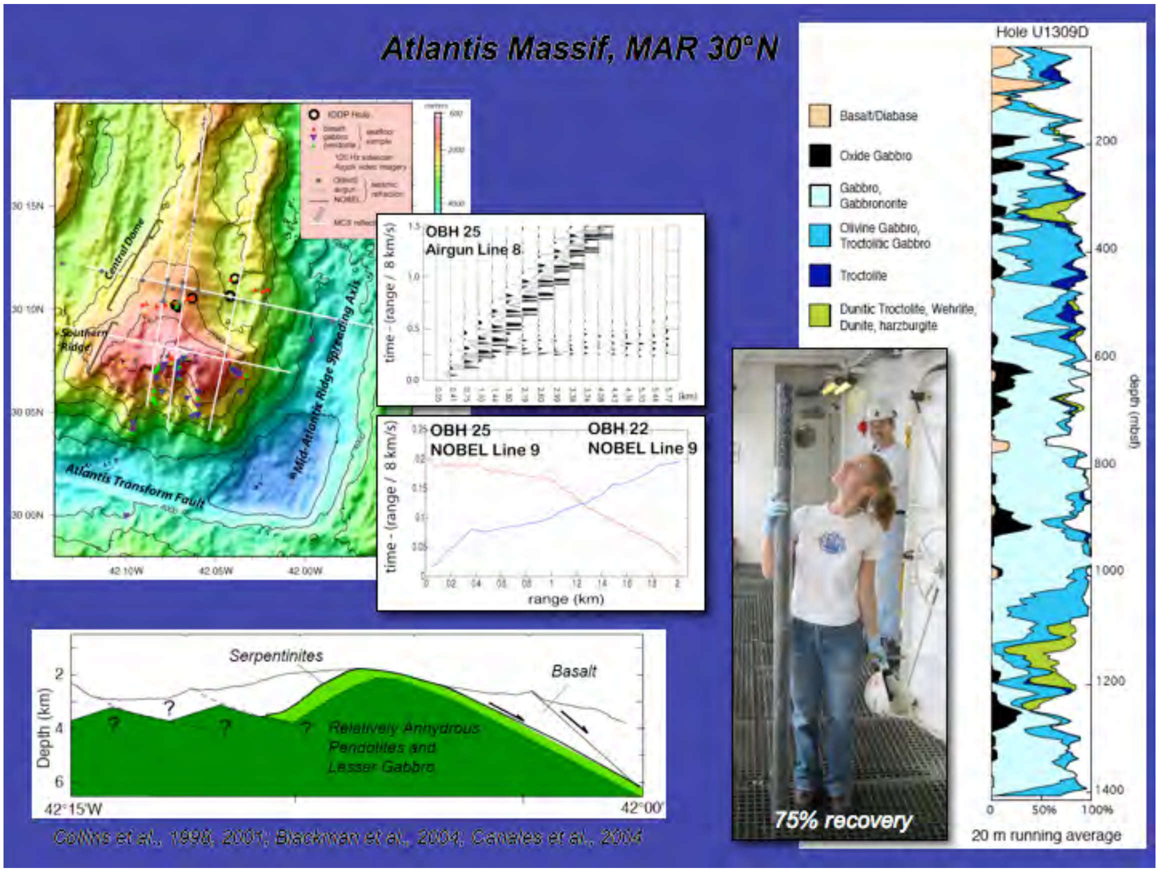
Kelley et al., 2005

Lost City

IODP Exp 305 scientific Party, 2005

Slide 10

Hole U1309D (Slide 10, 11) provided a considerable surprise to the geologic community, which on the basis of some very detailed seismic surveys, had expected to find fresh mantle peridotite there within several hundred meters of the seafloor. The thick gabbro section actually drilled, then may indicate that a massive gabbro body is intruding into mantle peridotite near the transform, as at Atlantis Bank, or that the lower crust is laterally heterogeneous on a scale of several kilometers.

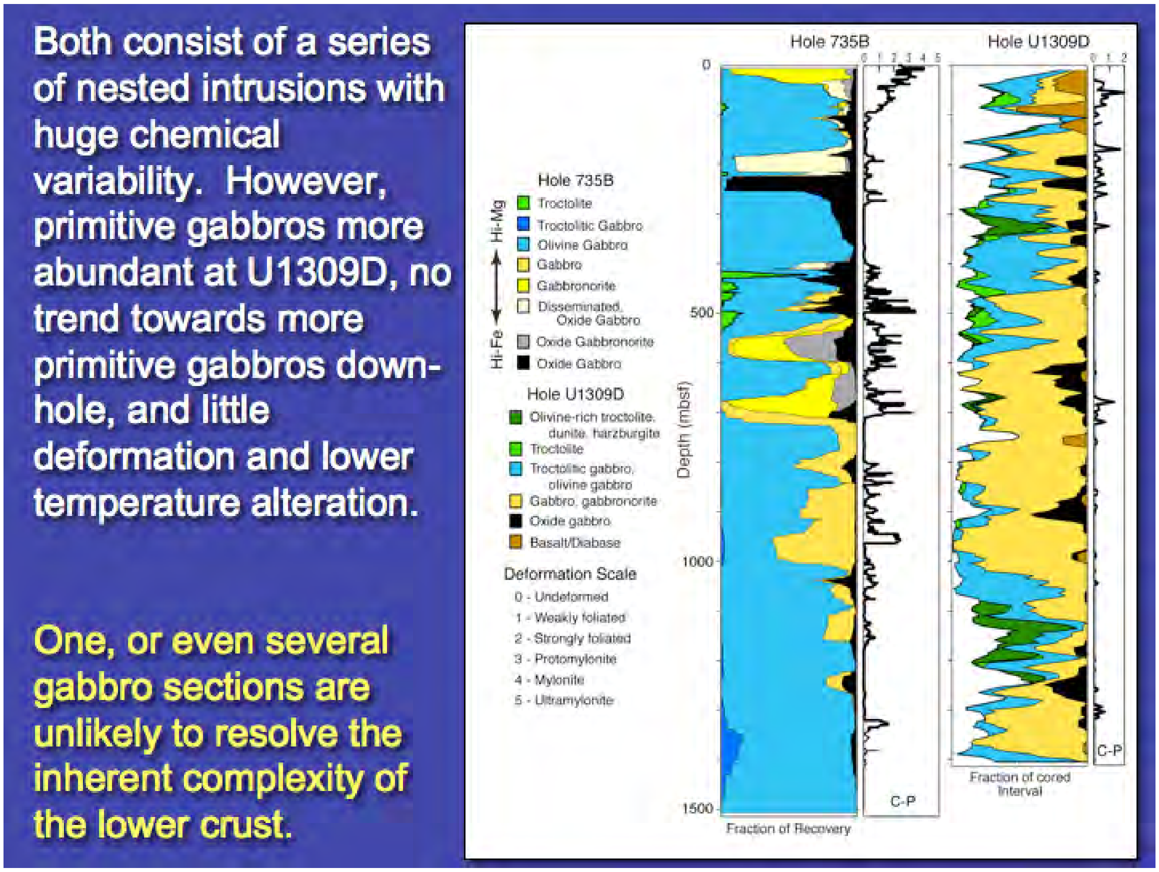


Atlantis Massif, MAR 30°N

75% recovery

Collins et al., 1998, 2001; Blackman et al., 2004; Canales et al., 2004

Slide 11



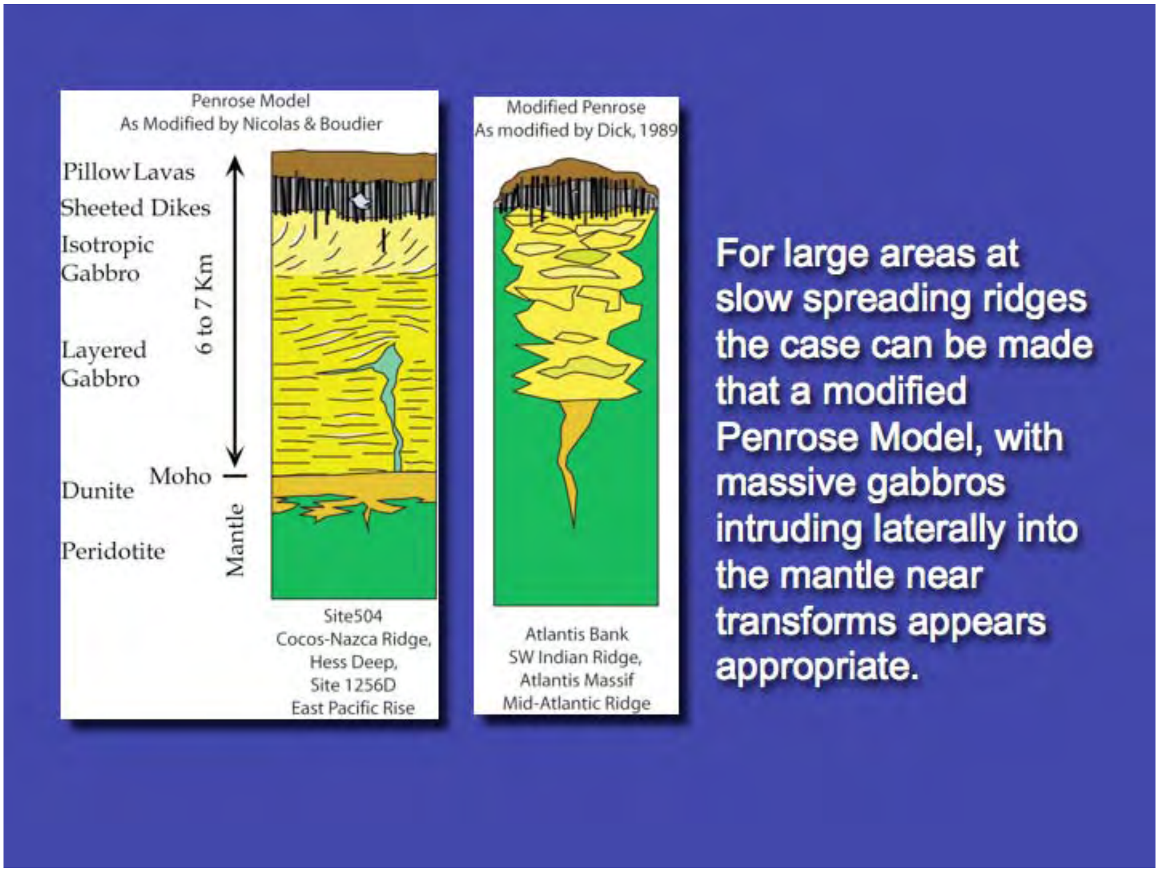
Both consist of a series of nested intrusions with huge chemical variability. However, primitive gabbros more abundant at U1309D, no trend towards more primitive gabbros down-hole, and little deformation and lower temperature alteration.

One, or even several gabbro sections are unlikely to resolve the inherent complexity of the lower crust.

Slide 12

While the igneous stratigraphy of Hole U1309D also consists of nested intrusions reflecting a complex magmatic history, the strong association of deformation and the occurrence of highly evolved gabbros at the top of the section found at Hole 735B does not exist there, and again, unlike, Hole 735B, there is no apparent systematic change in the composition of the section with depth towards more primitive olivine-rich gabbros. Rather primitive troctolites, more abundant than at Hole 735B, occur at all levels. In addition, whereas amphibolite facies alteration, largely in the upper portion of the hole, dominates Hole 735B, greenschist facies alteration dominates throughout Hole U1309D. This clearly demonstrates that drilling a single deep section of the lower crust in any magmatic environment (including the Pacific) cannot provide a full understanding of its nature.

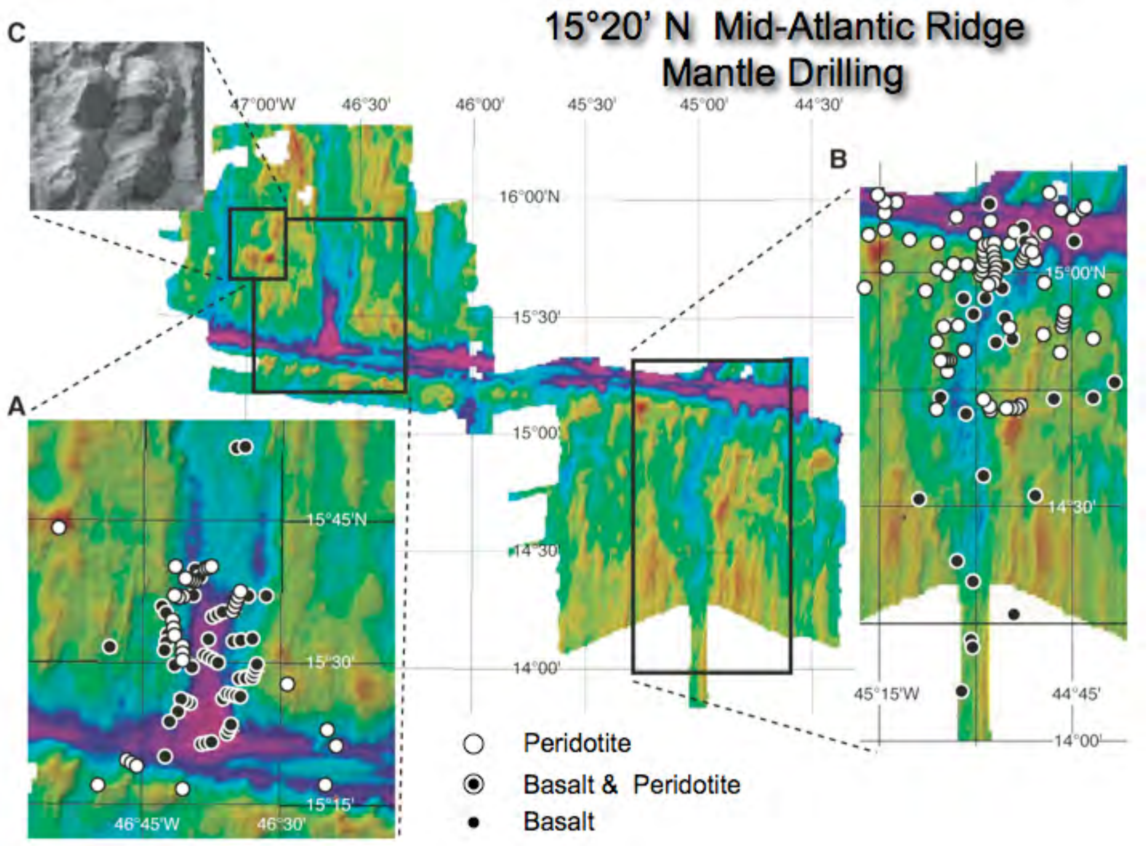
While Hole U1309D, due to thermal problems, is unlikely to provide an opportunity to drill to Moho, it remains open. This provides an opportunity to both obtain a longer and more representative section of the lower crust formed beneath the Mid-Atlantic Ridge, and to test the limits of drilling in a young hot ridge environment. Such a deep hole will also provide an opportunity for down-hole experimentation, and for obtaining a long thermal profile near an active ridge to test thermal models for this environment. However, it is also imperative that an offset hole is drilled nearby, sited to test whether or not the seismic prediction of relatively unaltered mantle rock nearby is correct, and to determine, if this is not the case, the lateral variability of the gabbro section. Since these objectives can be accomplished in a single leg, this should be done as soon as possible.



For large areas at slow spreading ridges the case can be made that a modified Penrose Model, with massive gabbros intruding laterally into the mantle near transforms appears appropriate.

Slide 13

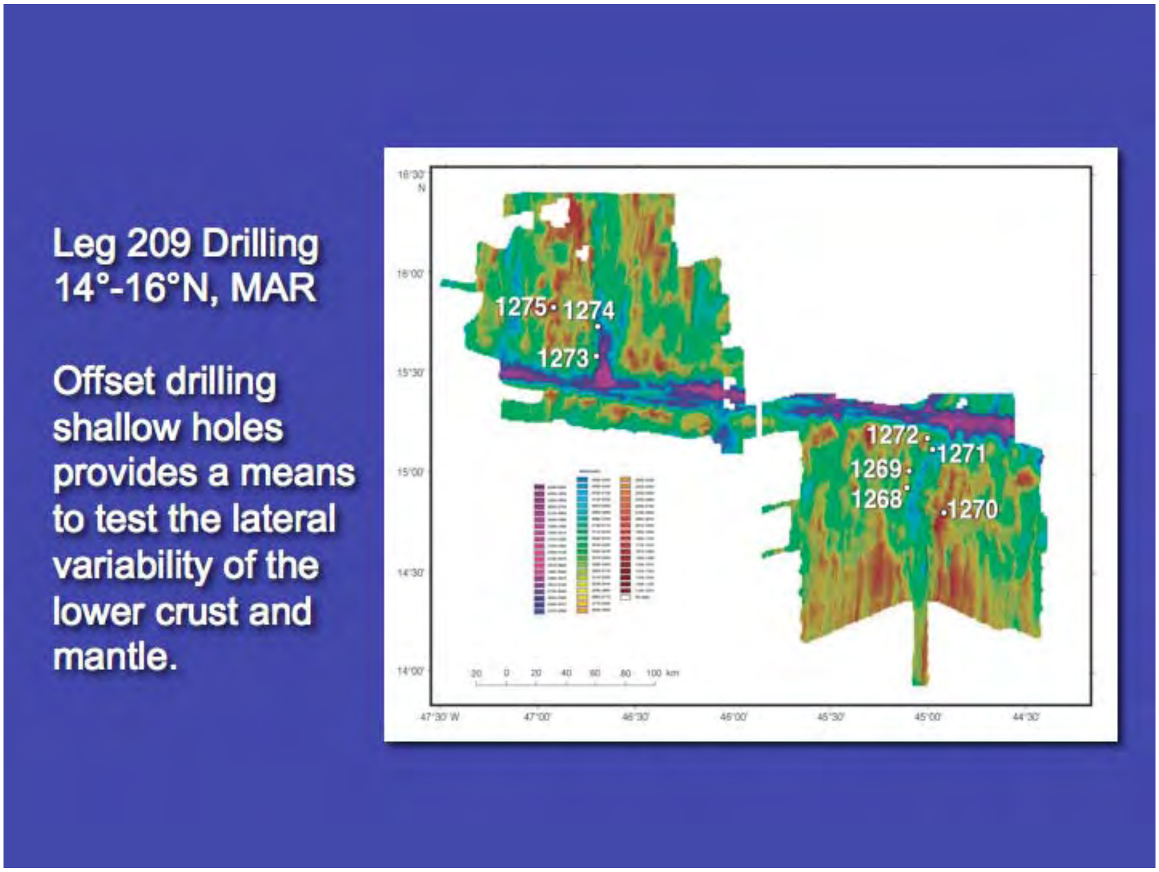
Drilling at Atlantis Bank and Atlantis Massif make a very strong case for a modified Penrose model (Slide 13), firmly entrenching this, as a second end-member for crustal architecture at ocean ridges.



15°20' N Mid-Atlantic Ridge
Mantle Drilling

Slide 14

However, ocean drilling to the north and south of the 15°20' F.Z. has found another end-member for the architecture of the ocean crust. In this region, numerous dredging and diving expeditions have found extensive outcrops of mantle peridotite on the seafloor both to the east and west of the ridge axis, and locally on the rift valley floor itself (Slide 14). Statistically, however, abundant gabbro has been recovered in the dredges with the peridotites, perhaps amounting to as much as 30-40% of all the plutonic rock exposed throughout the region. This led Mathilde Cannat and others, to propose that the ocean crust in this region was comprised of partially serpentinized mantle peridotite intruded by numerous small gabbro plugs, overlain by a thin discontinuous cover of pillow basalts.

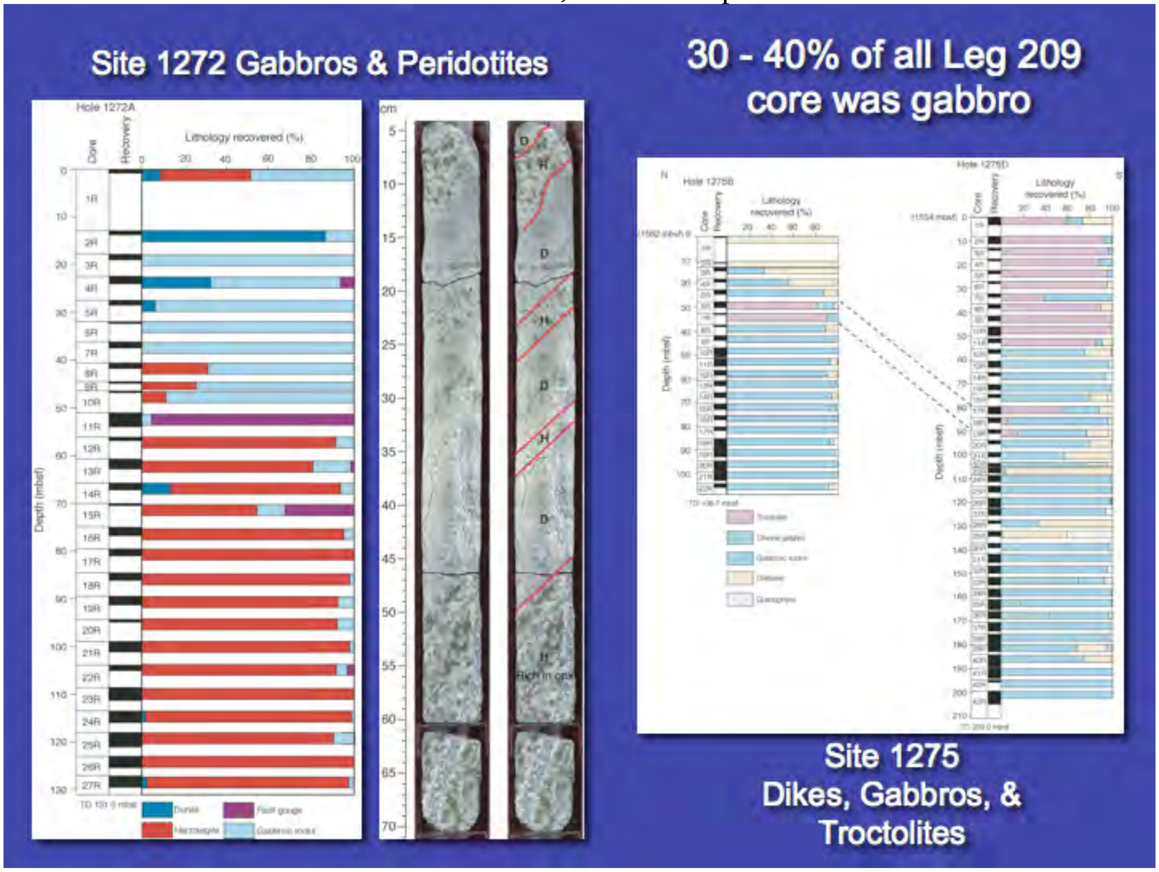


Leg 209 Drilling 14°-16°N, MAR

Offset drilling shallow holes provides a means to test the lateral variability of the lower crust and mantle.

Slide 15

Recognizing that the numerous outcrops of mantle peridotite afforded an opportunity to directly determine the fabric produced by emplacement of the mantle beneath an ocean ridge, ODP Leg 209 undertook the first systematic offset section drilling to look at the laterally variability of the mantle at the ridge segment scale, drilling at 8 locations offset to the north and south of the transform. It was anticipated that a systematic variation in the lattice preferred orientation of olivine would exist that would provide direct insight into the pattern of mantle flow beneath the ridges, such as the mantle diapirism implied by mantle fabrics in the Oman Ophiolite. Surprisingly, no systematic macroscopic pattern was found, and rather it appears that emplacement of the peridotites to shallow depths beneath the sea floor occurred through deformation confined to narrow zones within the mantle, rather than penetrative deformation.



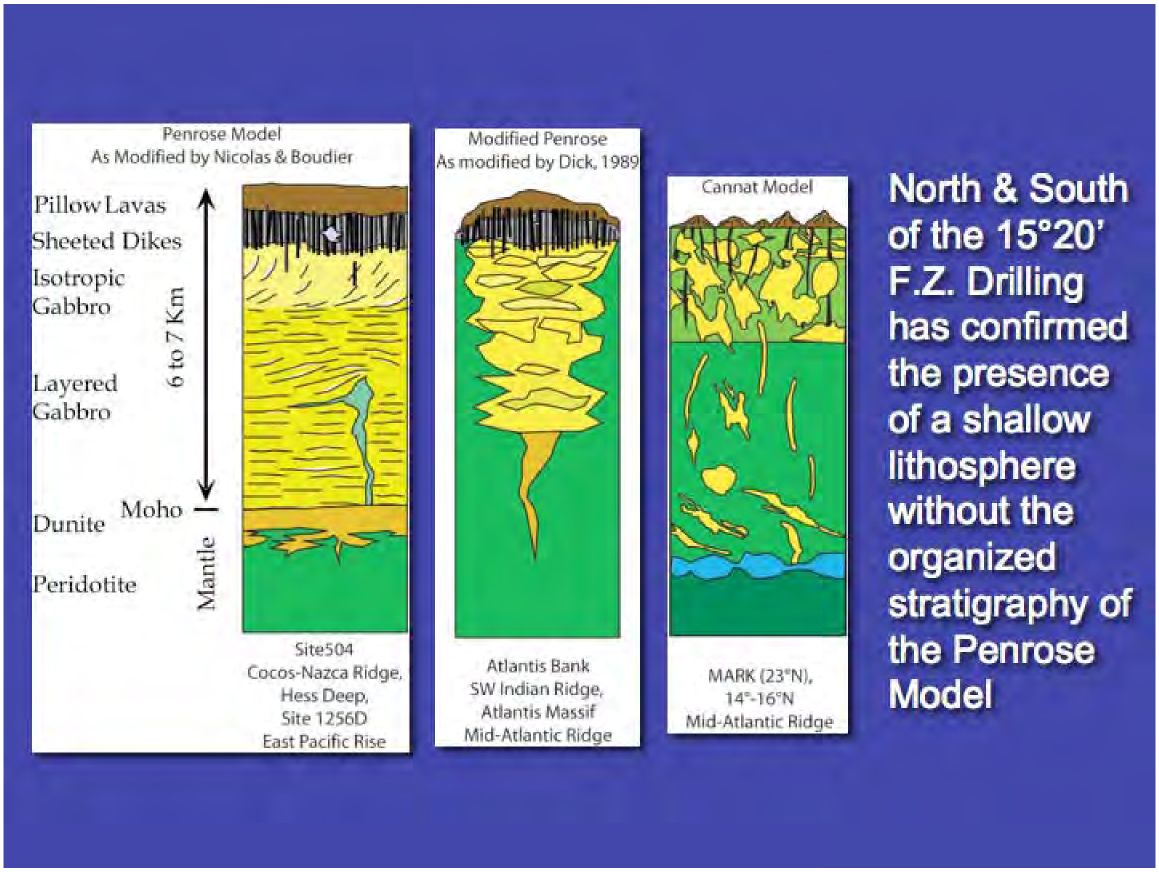
Site 1272 Gabbros & Peridotites

30 - 40% of all Leg 209 core was gabbro

Site 1275
Dikes, Gabbros, &
Troctolites

Slide 16

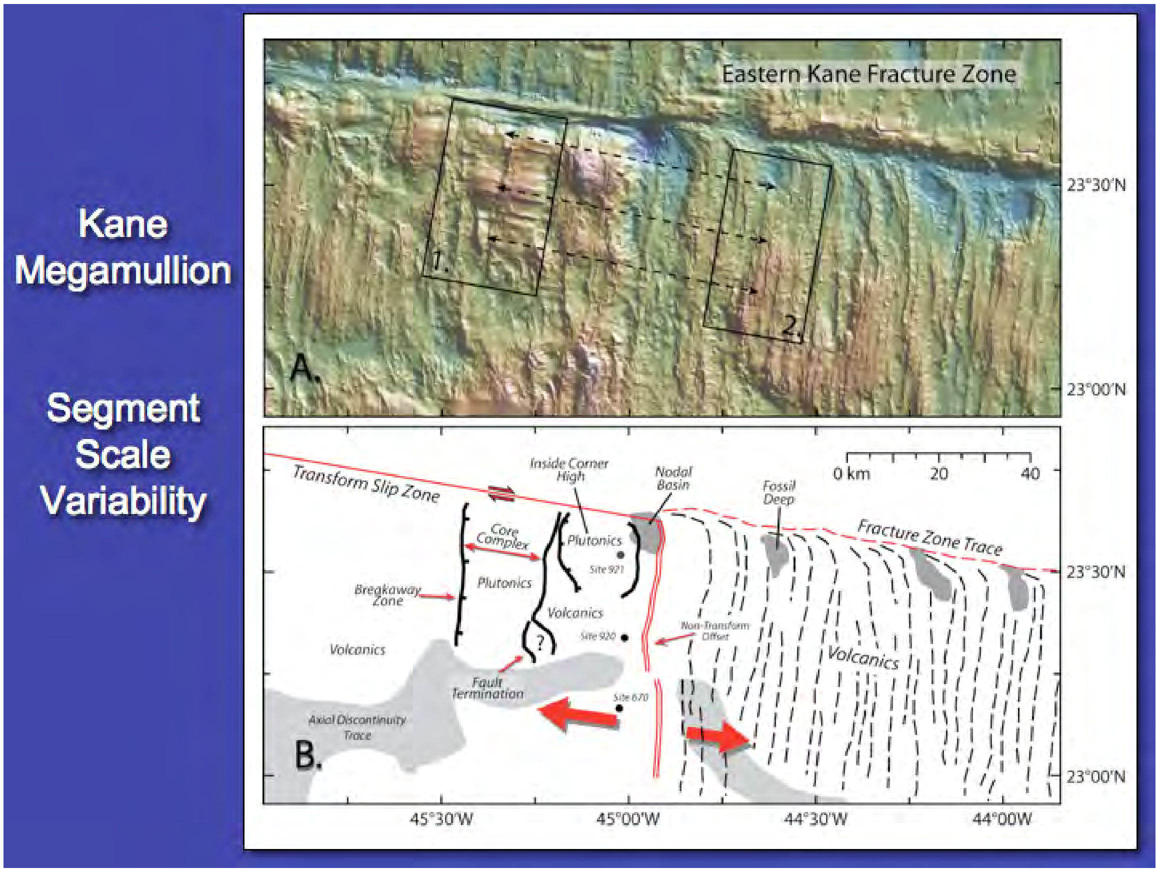
At the same time, however, drilling confirmed the inferences from surface geology, that the crust here does in fact consist of screens of mantle peridotite intruded by numerous gabbro plugs (e.g. Fig. 16), as proposed by Cannat and coworkers.



North & South of the 15°20' F.Z. Drilling has confirmed the presence of a shallow lithosphere without the organized stratigraphy of the Penrose Model

Slide 17

Thus, with the results of Leg 209, we have yet a third end-member for crustal accretion at ocean ridges: one not anticipated from earlier seismic studies of the ocean crust and the stratigraphy of “intact” ophiolites – leading to the conclusion that many “dismembered’ ophiolites, where parts of the Penrose sequence are missing, may not be dismembered at all, but representative of different intact ocean crustal architectures.

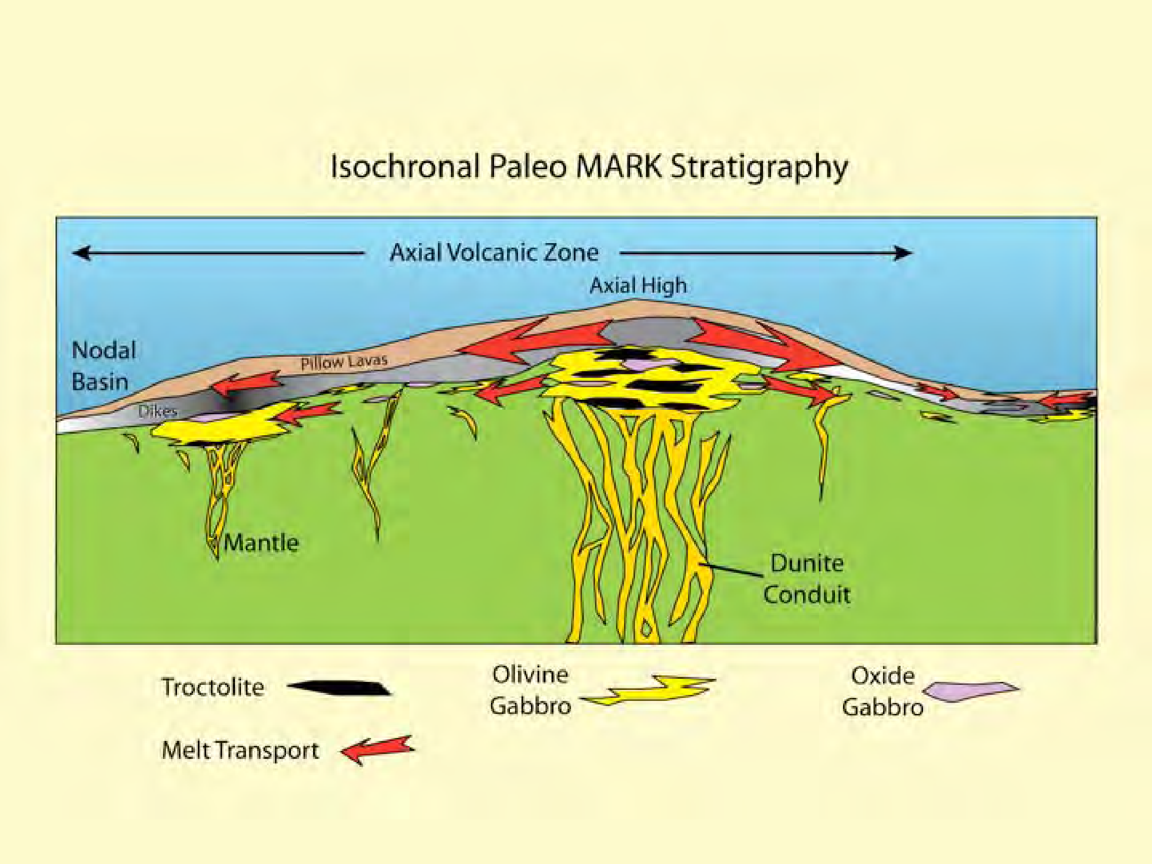


Kane Megamullion

Segment Scale Variability

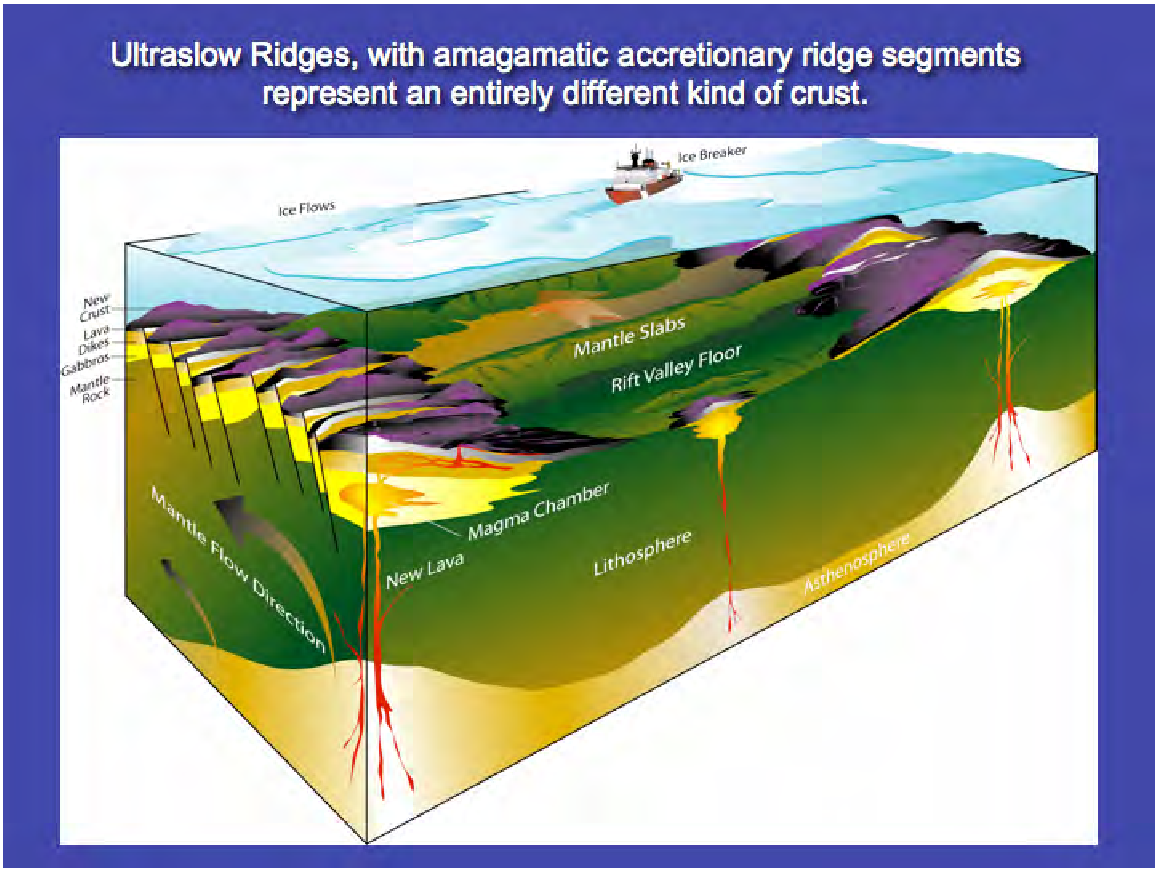
Slide 18

Tectonic windows also provide a unique opportunity to study the plutonic foundation of slow spreading ridges at the segment scale. Recent work at the Kane Megamullion south of the Kane Fracture Zone provides exposures of gabbro and peridotite that extend the full length of a slow spreading magmatic ridge segment. Moreover, due to the asymmetric spreading of the upper crust along the opposing lithospheric flow line from the one on which the core complex was emplaced, it is possible to directly correlate the lower crustal architecture exposed in the core complex, to the architecture of the shallow ocean crust on seafloor of the same age (Slide 18). In fact, recent ROV and dredging at the Kane Megamullion has shown that there is a systematic variation in the composition of the core complex from north to south. In the south, corresponding to the axial volcanic high preserved on the opposing tectonic plate, dunites and primitive troctolitic gabbros were sampled in abundance. The dunites, associated with harzburgite tectonites, represent the remains of melt transport conduits through the mantle to the crust, while the troctolites, which occur only rarely near the transform, represent primitive cumulates representing the early crystallization of mid-ocean ridge basalts emerging from the mantle. By contrast, to the north, while abundant peridotite has been dredged, dunites are rare or absent, while gabbros are more evolved. This, for the first time, directly supports a model for focused flow of melt out of the mantle to a ridge segment and then redistribution of melt laterally along the length of a ridge segment in the crust. Perhaps most surprising, however, is that the principle locus of intrusion of melt from the mantle, and the relict axial high are situated not far from the southern end of the segment, while sampling in the central region suggests that a significant gabbro layer was absent there.



Slide 19

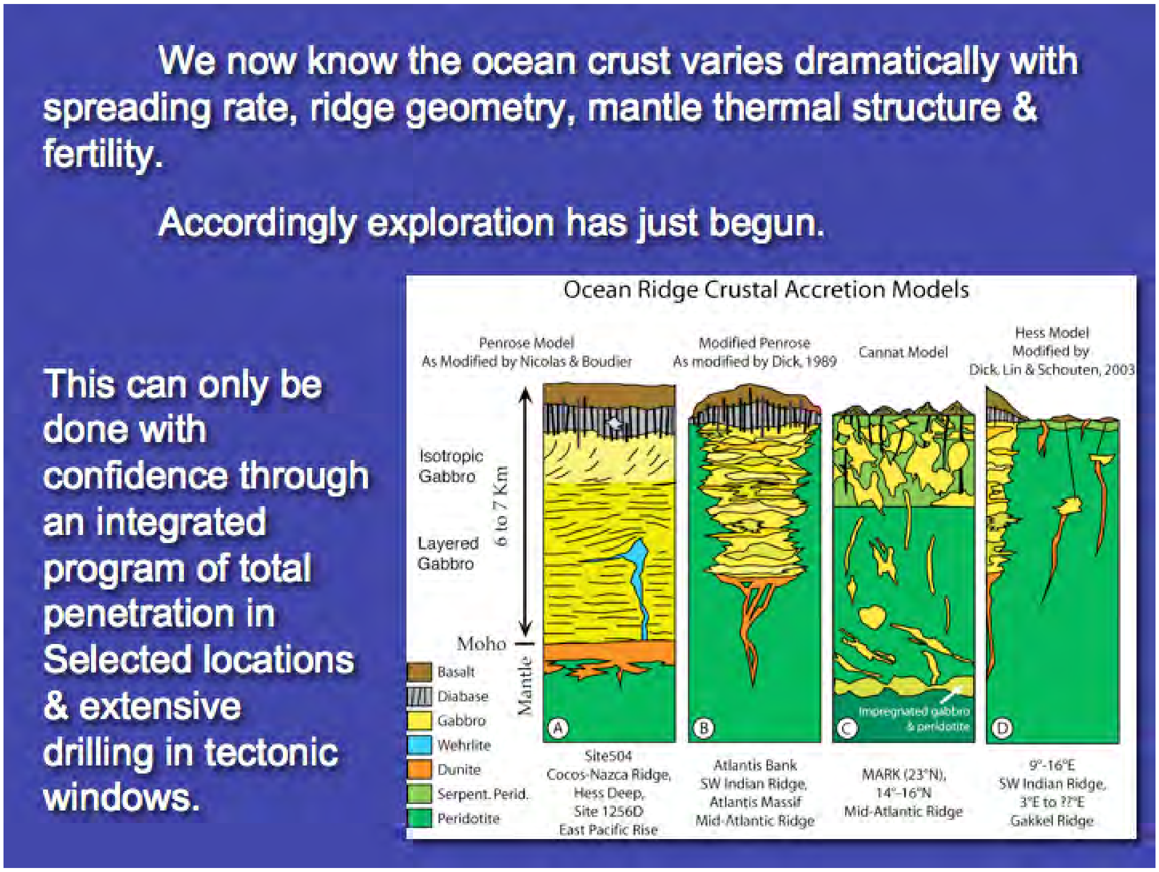
Such a stratigraphy, as illustrated in Slide 19, represents a radical departure from even the modified Penrose Model, suggesting that at a normal slow spreading ridge, significant areas of the ocean crust might consist of a dike and extrusive layer directly overlying the mantle. The rocks sampled on the Kane Megamullion, however, are all fault zone assemblages. The question is, then, are these actually representative of the true underlying crustal stratigraphy. Only a program of systematic offset drilling could determine this.



Ultraslow Ridges, with amagamatic accretionary ridge segments represent an entirely different kind of crust.

Slide 20

Finally, recent exploration along sections of the ultraslow spreading Gakkel and SW Indian Ridge have revealed a new kind of ocean crust. In these regions, amagmatic ridge segments where the mantle is emplaced directly to the seafloor with only scattered basalt flows have been found for long distances between major magmatic segments (Slide 20). Unlike the 15°20’ region, where large volumes of gabbroic rock have been sampled with the peridotites, gabbroic rocks are rare at the ultraslow spreading amagmatic segments.



We now know the ocean crust varies dramatically with spreading rate, ridge geometry, mantle thermal structure & fertility.

Accordingly exploration has just begun.

This can only be done with confidence through an integrated program of total penetration in Selected locations & extensive drilling in tectonic windows.

Slide 21

Thus, there are now reasonably well documented at least four major end-members for crustal architecture at the ocean ridges, each reflecting a different magmato-tectonic environment (Slide 21). This makes it clear, that determining the composition and architecture of the ocean crust requires more than a few total penetrations of the ocean crust, and that programs of deep penetration at specific locations in tectonic windows, and offset drilling to determine laterally variability will be required. At present the number of locations where such drilling is being proposed is fairly limited.

In all, a coherent program to drill the Moho, starting at a level just below the sheeted dikes may require about 4 legs. Deepening Hole U1309D in the Atlantic and drilling an offset hole: 1 additional leg. A program of offset drilling to test the lateral variability of crustal architecture at the segment scale at Kane Megamullion: 1 leg. An additional offset drilling leg at Hess Deep to capitalize on the unique opportunity there to look at the lateral variability of EPR lower crust and mantle: 1 Leg. Seven additional drilling legs over a ten year period. This, and assuming that other opportunities exist or will appear, suggest that a full program of offset drilling to complement a deep penetration in the Pacific, can be reasonably accomplished in parallel over the next ten to fifteen years of ocean drilling. Moreover, since a riser is not required for this drilling, it can proceed apace while the community waits for technology to catch up to objectives in the Pacific.

Age, Depth, Temperature, and Other Site Considerations for a Potential Whole-Crust Penetration

Douglas S. Wilson

Age, Depth, Temperature, and Other Site Considerations for a Potential Whole-Crust Penetration

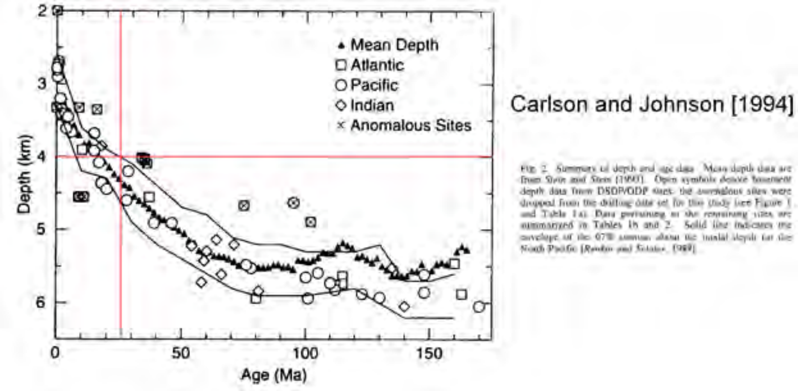
Doug Wilson, UCSB

Desired Site Properties:

- Not too deep (4-km riser)
- Not too hot at Moho (< ~200°C)
- Nearly normal ocean crust

- Need to settle for 2 out of 3

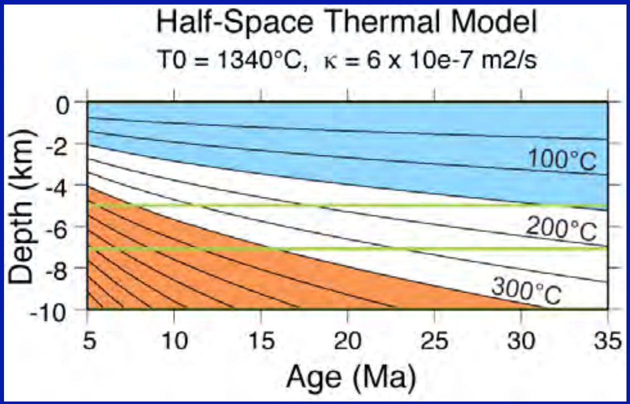
Observed Sea Floor Depth vs Age



Carlson and Johnson [1994]

Most sites subside deeper than 4000 m by 25 Ma

Predicted Temperature as a Function of Age and Depth



At 6 km, cooling below 200°C occurs after 25 Ma

Necessary Site Attributes

- Age > 15 Ma
- Depth < 4 km
- Intermediate to fast spreading rate, abyssal hill faults < 200 m high
- Weather window 9-12 months
- Simple, mapped tectonics

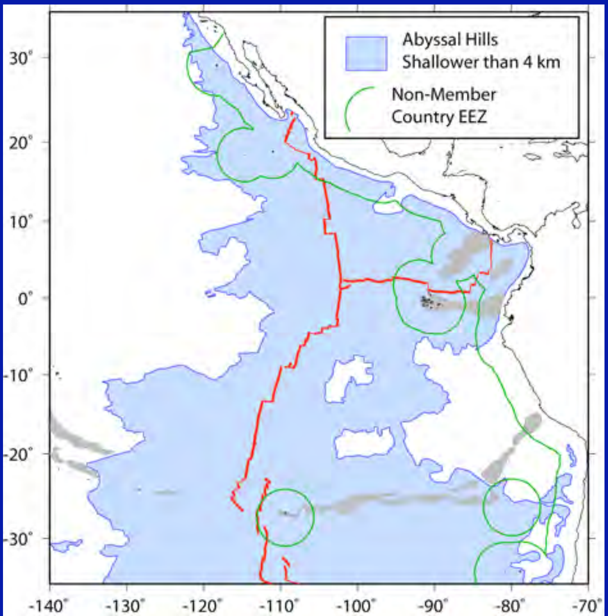
Necessary Site Attributes

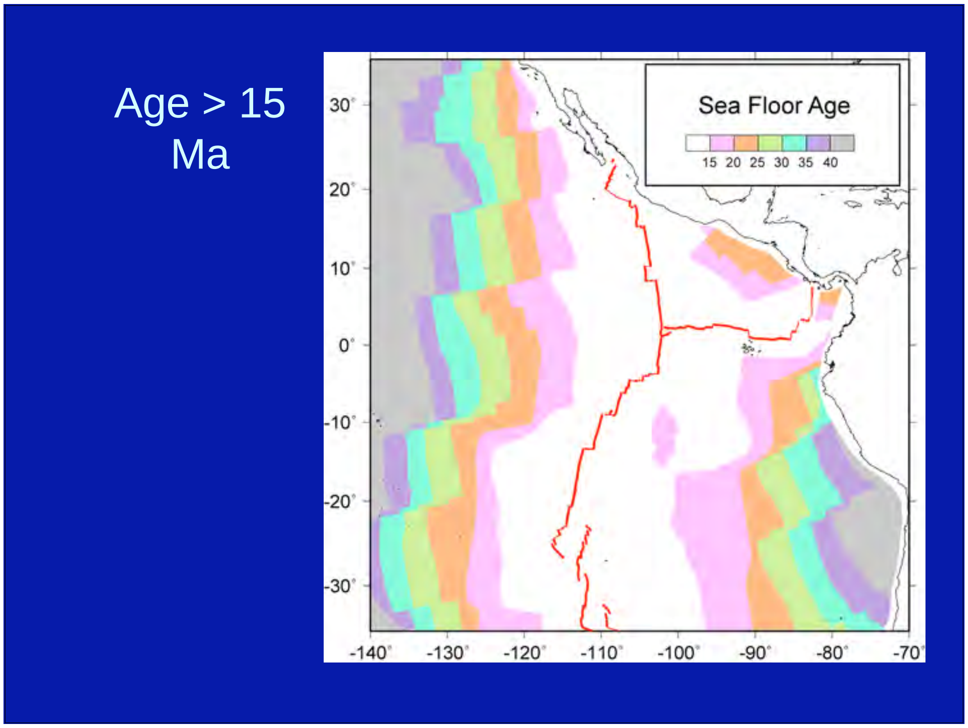
- Age > 15 Ma
- Depth < 4 km
- Eastern Pacific, 35°N–35°S
- Simple, mapped tectonics

Desirable Site Attributes

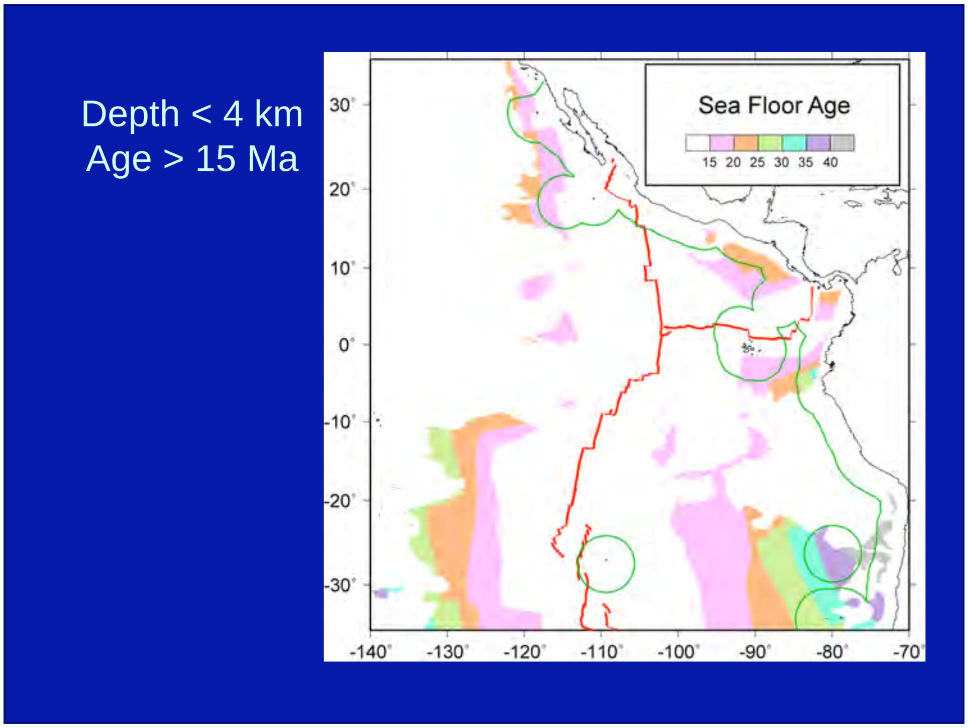
- Age > 20 Ma
- Close to major port(s)
- International waters or member EEZ
- Crustal thickness 5.0–5.5 km
- 12-month weather window
- Original latitude > ±15°
- Fastest available spreading rate

Depth limited by 4-km riser

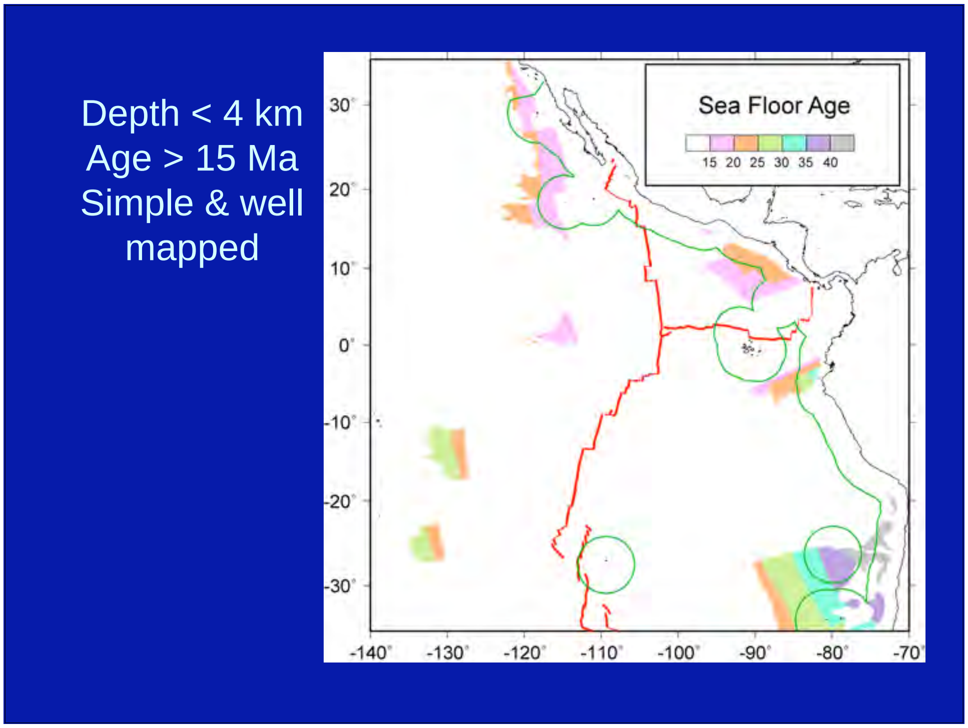




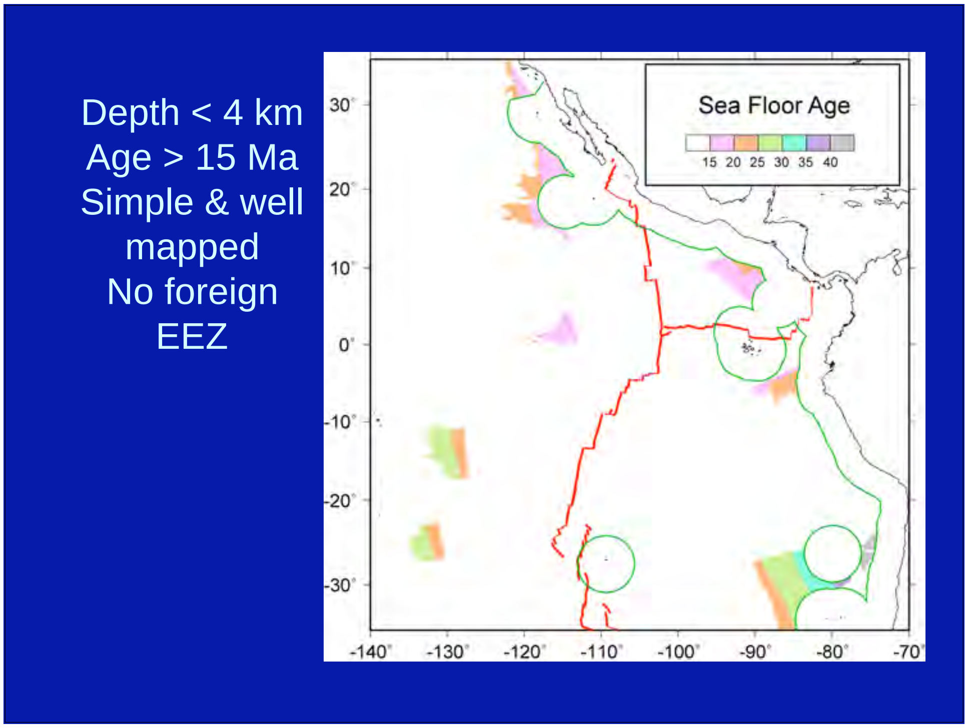
Age > 15 Ma



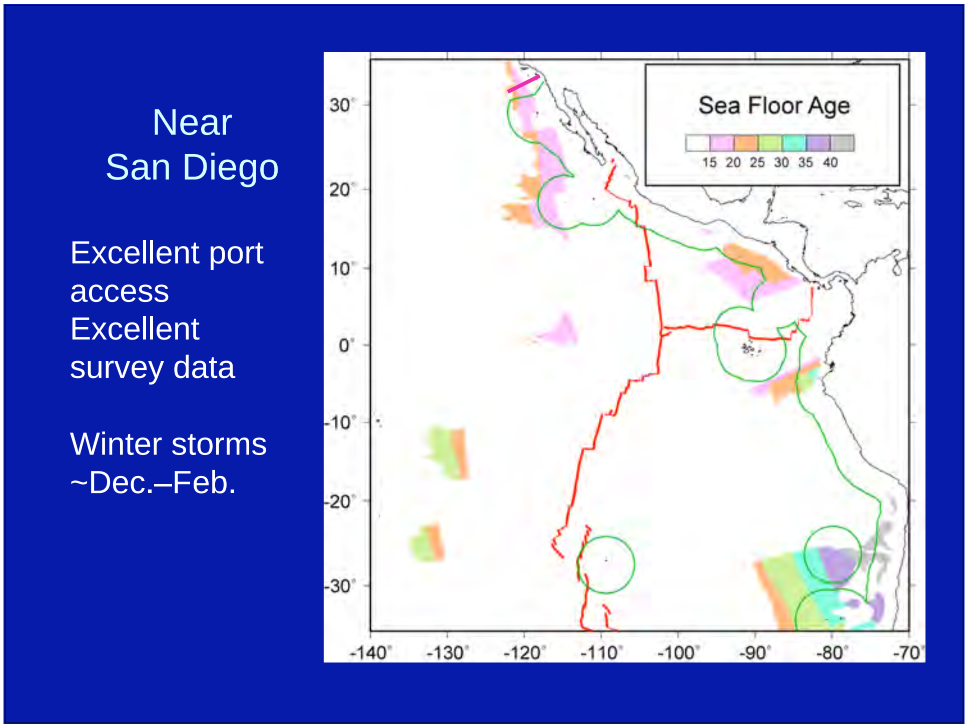
Depth < 4 km
Age > 15 Ma



Depth < 4 km
Age > 15 Ma
Simple & well mapped



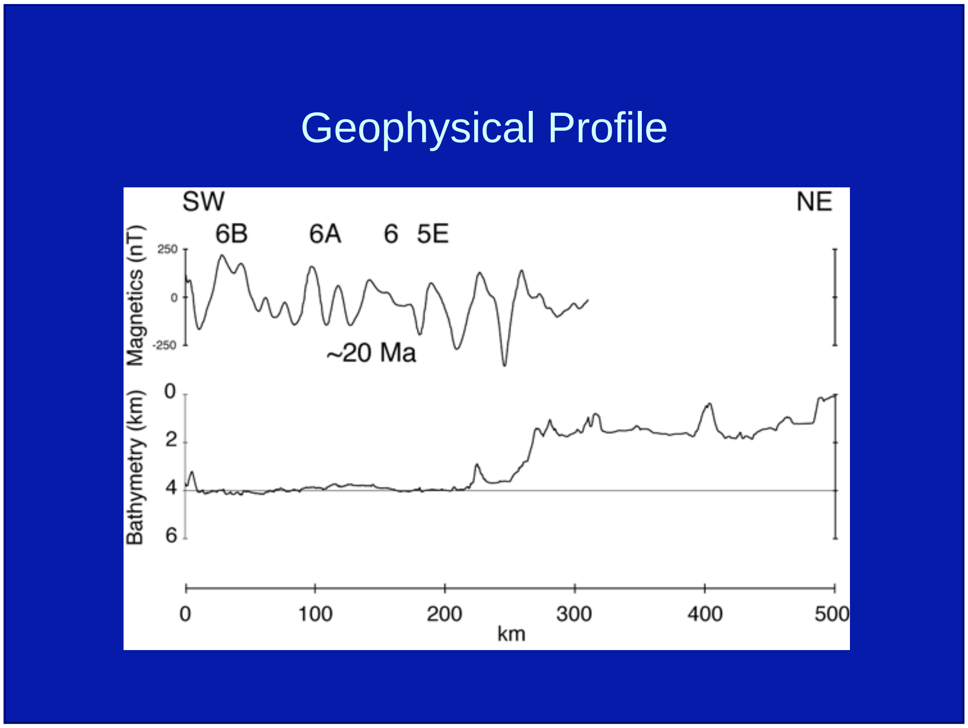
Depth < 4 km
Age > 15 Ma
Simple & well mapped
No foreign EEZ



Near
San Diego

Excellent port access
Excellent survey data

Winter storms ~Dec.–Feb.

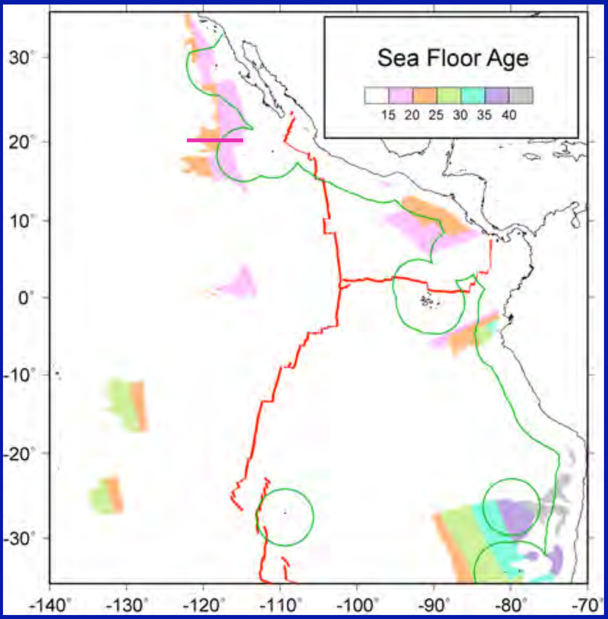


Geophysical Profile

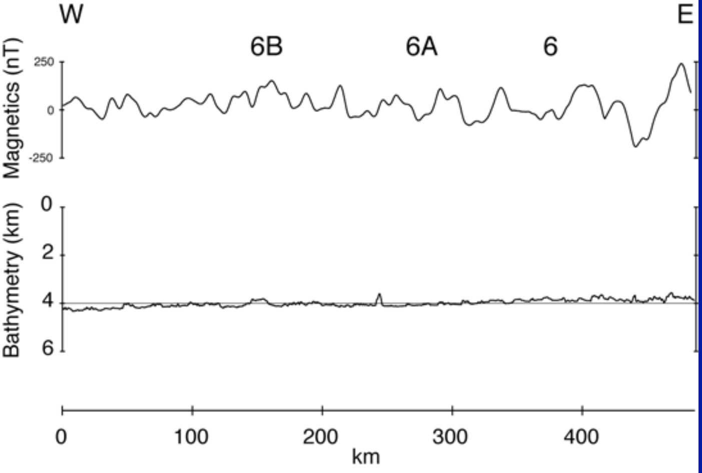
Clarion FZ

Decent port access

Limited survey data
Sediment thickness ~75 m
Tropical storms ~Aug.–Oct.



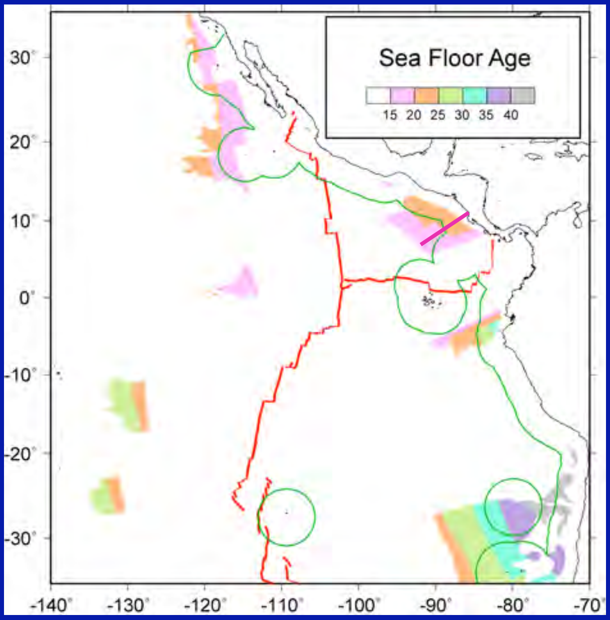
Clarion Profile



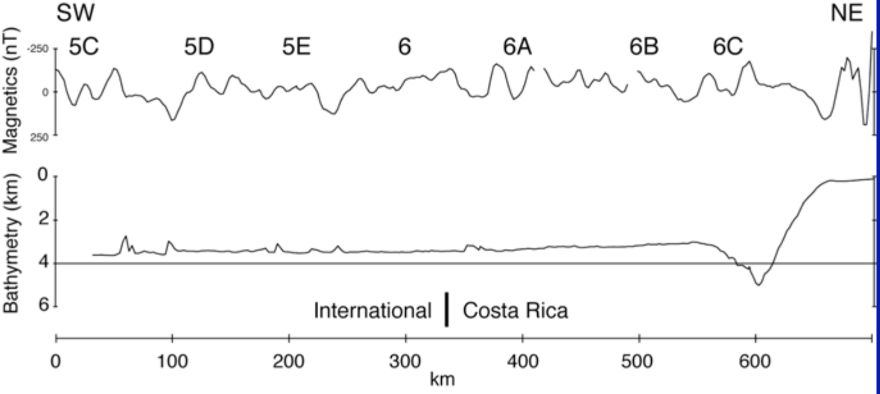
Cocos Plate Core

Good port access
12-Month weather window
Shallow:
~3500 m

Poor magnetic geometry
Strong tidal currents



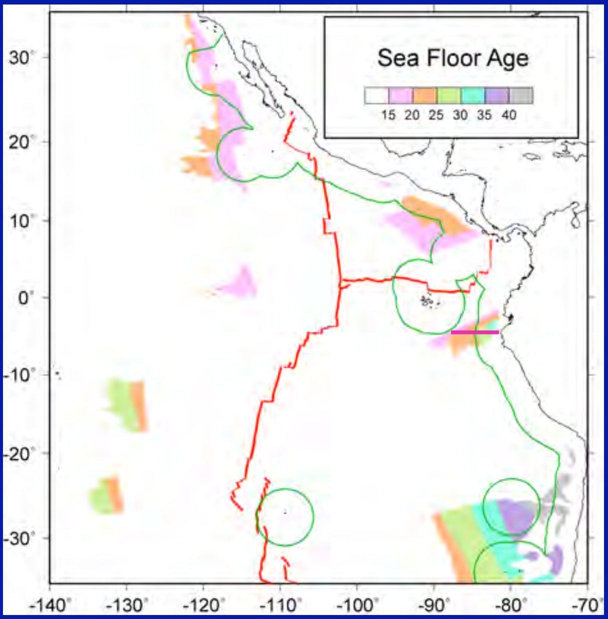
Cocos Plate Profile



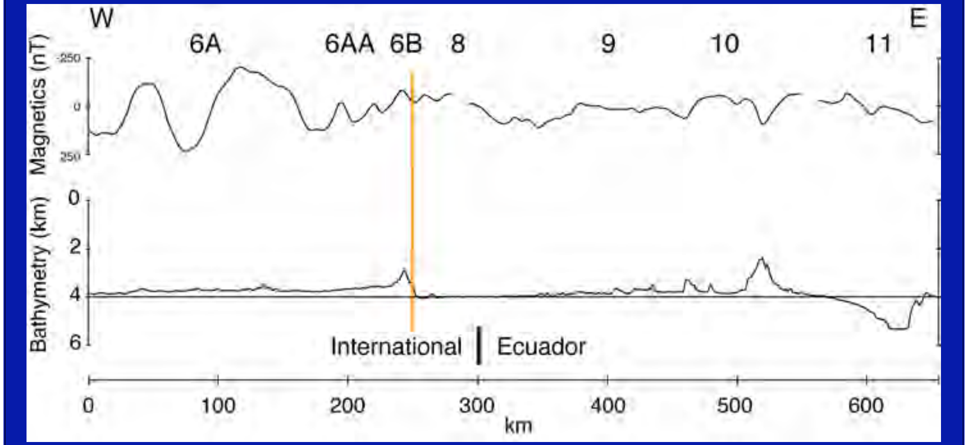
Grijalva Escarpment

Decent port access
12-Month weather window
Age > 25 Ma

Poor magnetic geometry
Hotspot influence; rifting



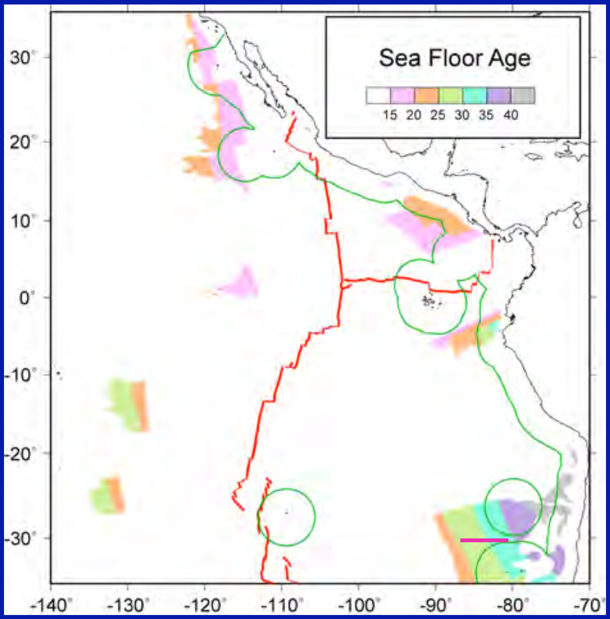
Grijalva Profile



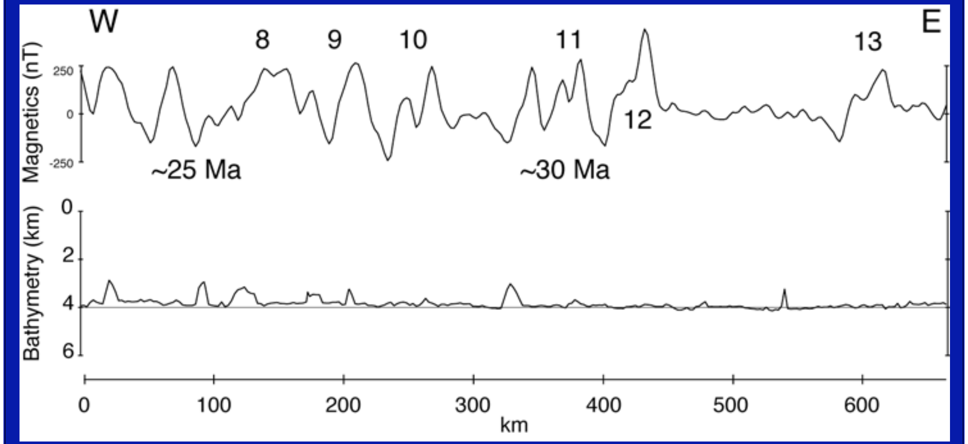
Near Valparaiso

Extensive ~30 Ma target area

Far from everywhere except Valparaiso



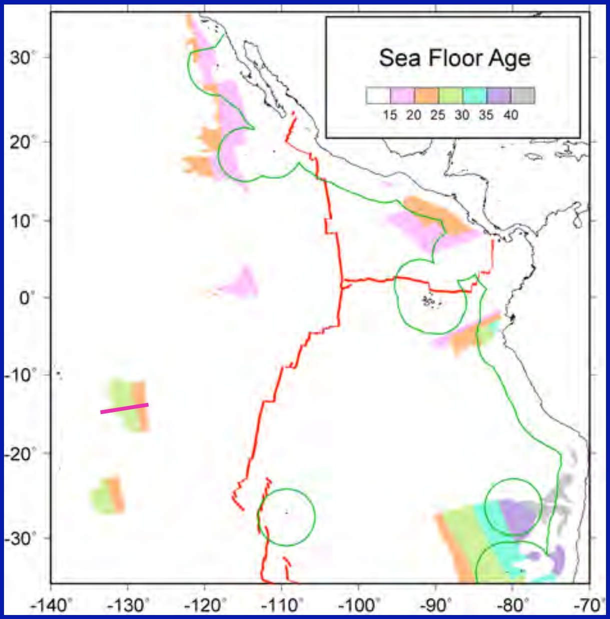
Valparaiso Profile



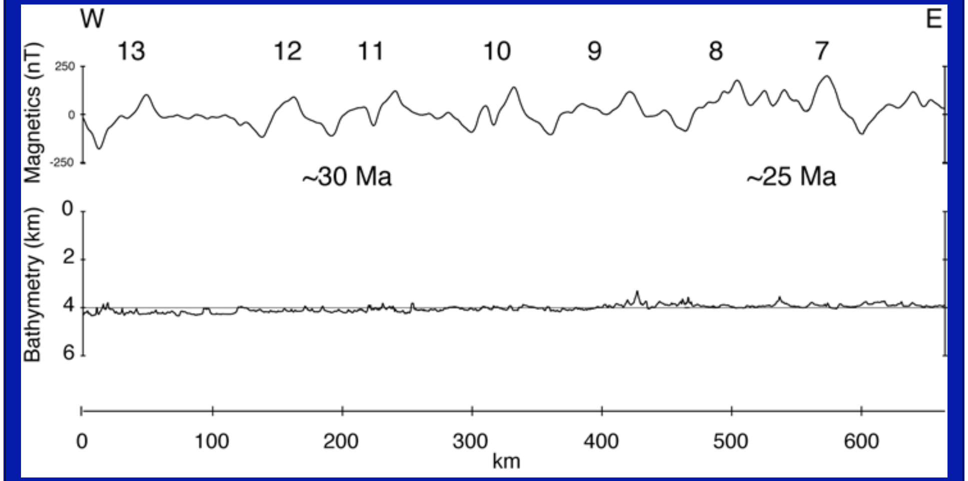
Marquesas-Austral Corridor

25–30 Ma target area

Far from everywhere except Tahiti



Marquesas-Austral Profile



Concluding Remarks

- To predict temperature at Moho, we need to measure thermal gradient & conductivity in seismic layer 3.
- To know depth limitations, we need testing of the deep riser.
- With added knowledge on points above, we can choose a site based on depth vs. age tradeoffs.

Extended Abstracts of Poster Presentations

- Direct petrological investigations on a megamullion (25°S Megamullion) in the intermediate-spreading Central Indian Ridge using the manned submersible SHINKAI 6500
  H. kumagai, K. Okino, T. Morishita, T. Sawagushi, K. Nakamura, N. Neo, M. Joshima, T. Shibuya, T. Sato, M. Takasu, S. Okada, K. Takai

- Magmatic processes under the ridges triggered by water: Experimental constrains
  J. Koepke

- Structure of Oceanic Crust and Moho of the Pacific Plate around the Ogasawara Plateau
  T. Tsuji, Y. Nakamura, H. Tokuyama, M. Coffin, and K. Koda

- Igneous petrology of site U1309, IODP Expedition 304/305 at Atlantis Massif, MAR 30°N: preliminary analysis of peridotites
  A. Tamura, S. Arai, E.S. Andal, S. Ishimaru, N. Abe, K.T.M. Johnson, D. Brunelli, H. Hansen, E. Hellebrand and the Expedition 304/305 Shipboard Science Party

- Oceanic Core Complexes and Crustal Accretion at Slow-Spreading Ridges. Indications From IODP Expeditions 304-305 and Previous Ocean Drilling Results
  B. Ildefonse, D. Blackman, B.E. John, Y. Ohara, D.J. Miller, C. MacLeod and IODP Expeditions 304/305 Science Party

Direct petrological investigations on a megamullion (25°S Megamullion) in the intermediate-spreading Central Indian Ridge using the manned submersible *SHINKAI 6500*

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(1) JAMSTEC, (2) The University of Tokyo, (3) Kanazawa University, (4) Shohoku College, (5) Niigata University, (6) AIST, (7) Tokyo Institute of Technology, (8) NME co.
*: presenting author

Abstract

We preset the first results of direct observation and sampling combined with detailed bathymetric studies on a megamullion in the intermediate-spreading Central Indian Ridge (25°S Megamullion) using *SHINKAI 6500* of JAMSTEC. A corrugated surface parallel to the direction of plate motion is well observed on dome-like exposure. Recovered samples from the top surface of the Megamullion demonstrate that the striated outcrop is associated with high-strain cataclasite to cataclastic mylonites with foliation subparallel to the surface. Corrugated surfaces are, therefore, expected to be exposed detachment faults. The presence of relatively less deformed rocks beneath the top surface indicates that deformation is highly localized on the detachment fault. Serpentinized peridotites and gabbros were recovered, suggesting that they are exposing oceanic lower crust and upper mantle along the detachment fault. Serpentinized peridotites are less abundant in modal amount of clinopyroxene as compared with those recovered from slow-spreading ridges, indicating that degree of partial melting is higher in the studied samples than in slow-spreading ridges. Intermediate-spreading ocean ridges are not formed by an intermediate magmatic activity but are probably formed by dynamic switching between high-magmatic activity and low-magmatic activity periods (magmatic and amagmatic ocean floor generations).

1. Introduction

Recently discovered megamullions on ocean floor, dome-like exposure with a corrugated surface parallel to the direction of plate motion, have been interpreted to be the exhumed footwalls of long-lived detachment faults operating near the ends of spreading segments where limited magmatism is expected (e.g., Tucholke et al., 1998). Brittle deformation is key to forming topography, controlling crustal structure, and exposing lower crust to upper mantle rocks. Megamullion provides excellent opportunities to investigate deep sections of the crust and the upper mantle, fault evolution including strain localization, and thereby to constrain fundamental tectonic processes in ocean crust, in particularly at low-magmatic activity area.

Data on megamullions (or oceanic core complex) have been, however, restricted mainly to the Mid-Atlantic Ridge (e.g., Blackman et al., 1998; Tucholke et al., 1998), two localities (Atlantis Bank and Fuji dome) on Southwest Indian Ridge (Dick et al., 2000, Baines et al., 2003, Searle et al., 2003) and one locality on the Parece Vela backarc basin (Ohara et al., 2001). We conducted three Japanese submersible *SHINKAI 6500* dives on a megamullion in the intermediate-spreading Central Indian Ridge at 25°S (termed 25°S Megamullion hereafter) and obtained visual, rock samples along a transect from near the termination extending towards the breakaway (Fig. 1). This is the first report on detailed petrological investigations on the 25° S Megamullion from the Central Indian Ridge.

2. Geological Setting of 25° S Megamullion

The Central Indian Ridge (CIR) is an intermediate-spreading mid-ocean ridge with spreading rates from 30 mm/year (full rate) near the equator to 49 mm/year at the Rodrigues Triple Junction (DeMets et al., 1990; Hellebrand et al., 2002). We conducted the first submersible dive program designed to investigate one of these features systematically. We chose a well-developed megamullion, here termed 25 ° S Megamullion, on the Central Indian Ridge.

The 25°S Megamullion, 23 km x 13 km in size, is located at the boundary between the first segment and the second segment just west of the active CIR (Fig. 1). The bathymetric “corrugations” on the dome surface have wavelengths of ~ 1-1.5 km, and lengths of several kilometers (Fig. 1). The slopes around the ridge-facing fault are steep and show numerous mass-wasting scarps expose deeper structural levels of the footwall as described later.

3. Sample descriptions

Samples collected from the 25°S Megamullion are classified into basalts including dolerites, gabbros, peridotites, plagiogranite, and deformed rocks as described below.

3.1. Basalts (dolerites)

Basalts including dolerites were recovered in all dives. Basaltic samples recovered beneath the top surface of the Megamullion basically suffered from variable degree of metamorphism and weathering (Fig. 2a) whereas fresh basalts were recovered on the top surface of the Megamullion. Basaltic debris is scattered across the top surface, either partially buried or sitting on the sediment. The scattered rocks some times occur in clusters or in elongated "fensces". These features were also reported from other megamullion (Tucholke et al., 2001).

3.2. Gabbros

Gabbros were recovered in all dives. It is noted that gabbros were also recovered just below the top surface of the Megamullion. Gabbros are massive with variations both in composition (gabbro to oxide-rich gabbro) and grain size at the scale of individual samples (Fig. 2b). Some gabbros are amphibolitized and are further locally altered under green schist facies conditions. Microstructural show magmatic textures, usually with no or very minor plastic deformation except for very localized mm-scale shear zones in altered gabbros.

3.3. Peridotites

Two serpentinized peridotites (Fig. 2c) are recovered along the ridge-facing slope. These peridotites have been static serpentinized and show the typical serpentine mesh texture replacing olivine crystals, serpentine pyroxene pseudomorphs. Modal amount of clinopyroxene is low in the both samples. Plagioclase pseudomorph is observed in the samples. These peridotites were intruded by gabbroic veins (Fig. 2c) which frequently contain zircons. Recovery of serpentinites implies that mantle rises steeply and is exposed on the ocean floor by the detachment fault. Serpentinized peridotites were also sampled at Green Rock Hill, located off-axis on the western flank of the southernmost CIR segment (Hellebrand et al., 2002).

3.4. Plagiogranites

Small amount of felsic rocks, quartz diorites, tonalities, trondjhemites, so-called oceanic plagiogranites (Coleman and Donato, 1979) were sometimes found from ocean floor. Plagiogranitic rocks were recovered in two dives. One representative sample (Fig. 2d) is composed of quartz (43 vol. %), plagioclase (Ab_{85-95} An_{5-10} Or_{1-6}) (55 vol. %) and amphibole (2 vol. %) with small amount of epidote including allanite, titanite, apatite and zircon.

Geochecmial characteristics of the sample are high in SiO_2 content and low in TiO_2, K_2O, total FeO and P_2O_5 contents. Chondrite-normalized REE patterns show highly evolved signature. Origin of felsic magmatism beneath ocean floor is still in controversial (e.g., Koepke et al., 2004).

3. 5. Deformed rocks

Recovered samples from the top surface of the Megamullion demonstrate that the striated pavement (Fig. 3a,b) is associated with high-strain cataclasite to cataclastic mylonites with foliation subparallel to the surface (Fig. 3c,d). The mineral assemblages found in the fault rocks imply alteration of basalts and peridotites under greenschist facies conditions and a substantial fluid flux both prior to and during deformation. Penetration of fluids along permeable pathways in the upper lithosphere is likely to induce marked weakening upon formation of serpentine and range of other secondary minerals (e.g., talc, chlorite), localizing strain very efficiently onto large, discrete shear zones within the shallow lithosphere.

4. Discussions

Megamullions have two prominent characteristics: (1) a gently domed, overall turtleback shape (i.e., megamullion) and (2) a surface that is interpreted to be a single and extensive fault plane that is distinguished by the presence of prominent corrugations (mullion structures) that parallel the fault slip direction (e.g., Tucholke et al., 2001). These features are well observed in the 25°S Megamullions. Furthermore, striations at cm-scale parallel to the spreading direction, which are also reported from other megamullions (MacLeod et al., 2002), are also observed at basement outcrops at the top surface of the detachment. The presence of relatively undeformed and unaltered rocks immediately beneath the detachment fault surface indicates that deformation is highly localized on the detachment fault. Serpentinized peridotites and gabbros were interpreted to be exposing oceanic lower crust and upper mantle along the detachment fault. Our results suggest that megamullions are not restricted to slow-spreading ridges but are probably more frequently distributed on the ocean floor.

Peridotite rocks were now though to be more widely exposed on the ocean floor than expected before, particularly in the slow-spreading ridges, where magmatic activity is low (e.g, Michael et al., 2003). Mid-ocean ridges that have limited magma supply are strongly affected by normal faulting that creates rough abyssal hill topography, e.g., megamullions. It is interesting to note that degree of partial melting of peridotite samples from the 25°S

Megamullion is higher than that from slow-spreading ridges. In the 25°S Megamullion, peridotites expected to be formed at relatively high magma activity period are now tectonically exposed along the detachment fault. Our observations coupled with the previous works on the slow- and fast-spreading ocean ridges suggested that the studied area was not formed by an intermediate-magmatic activity but was probably formed by dynamic switching between relatively high-magmatic activity and low-magmatic activity periods. (magmatic and amagmatic ocean floor generations).

Acknowledgements: We are grateful to Captain Ishiwata and the crew of the Yokosuka and the SHINKAI team who contributed to the success of the URANIWA cruise. Support for this work was provided by the JAMSTEC. T.M. thanks Kaori Hara for making several thin sections in this study.

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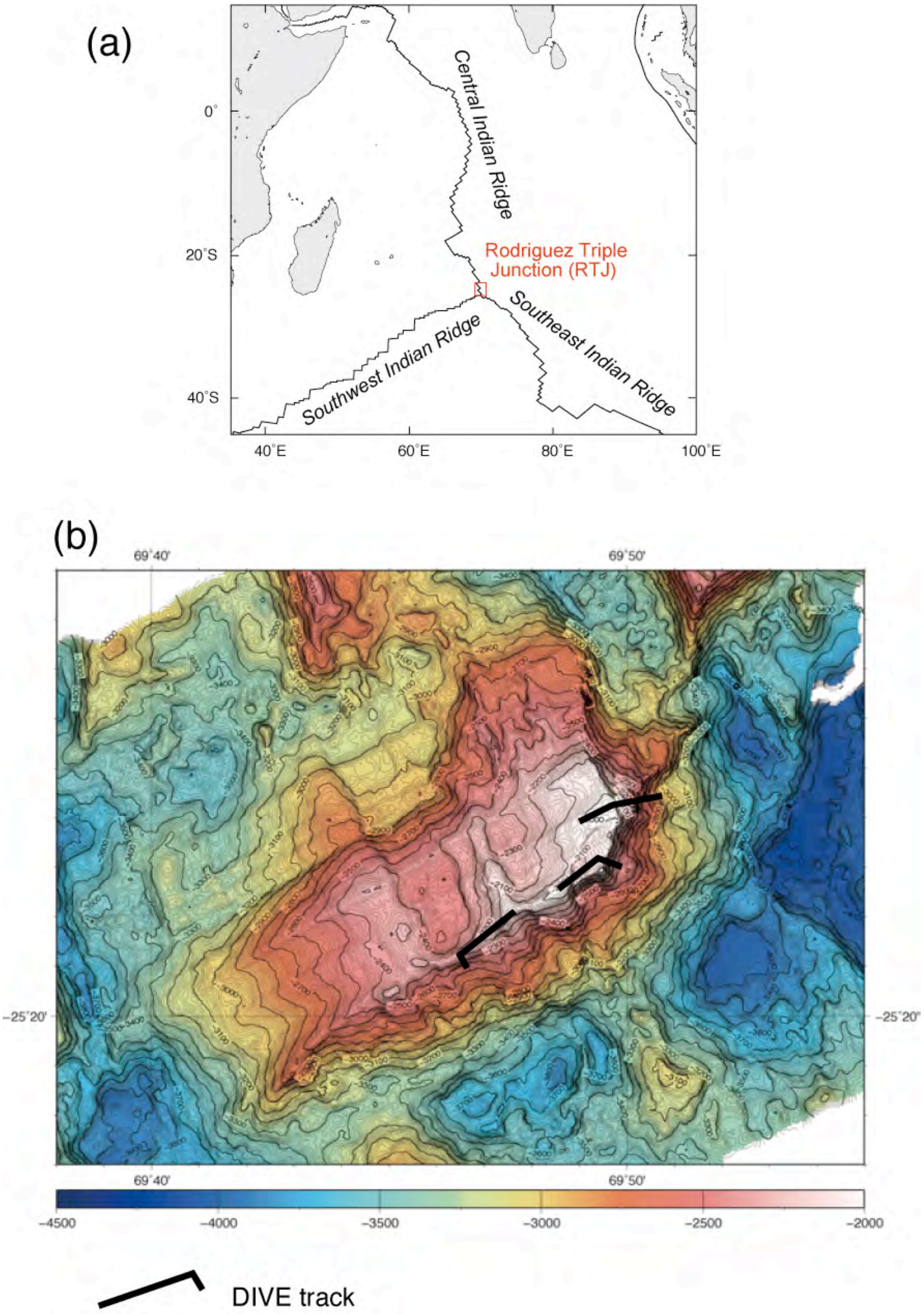

Figure 1. (a) Location of the study area on the Central Indian Ridge. Portions of the Southwest Indian Ridge and Southeast Indian Ridge are also shown. (b) Bathymetric map of the 25°S Megamullion (prepared by K. Okino and shown in Kumagai et al. 2006). Dive trace of no. 919, 920 and 921 are also shown.

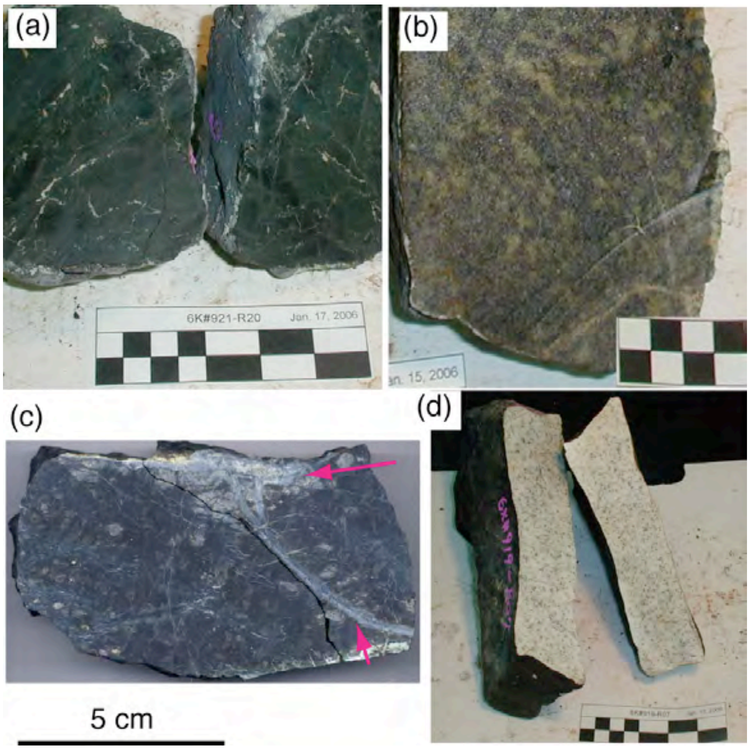

Figure 2. Representative recovered samples from the 25°S Megamullion. (a) Highly altered basalt. A part of white veins (b) Massive, less altered gabbro. (c) Highly serpentinized peridotite intruded by gabbroic veins (indicated by arrows). (d) Plagiogranite.

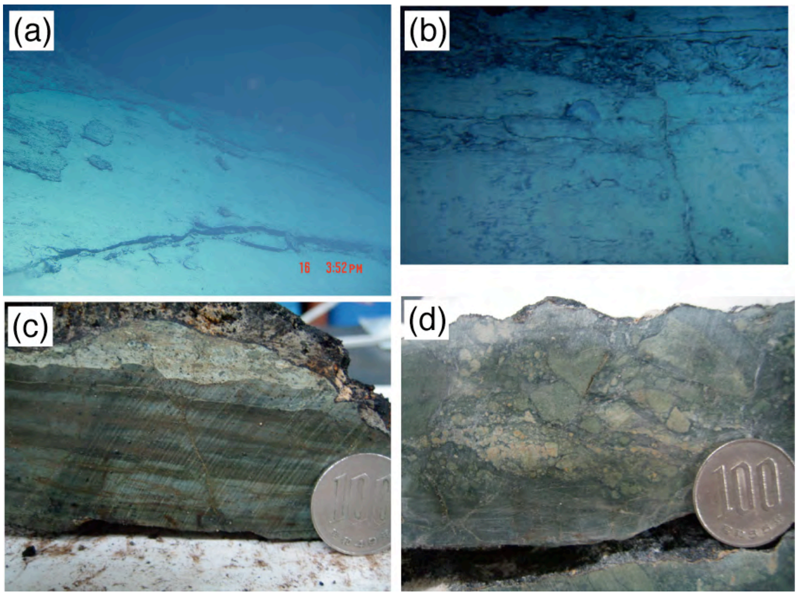

Figure 3. Occurrences and lithologies of the top surface of the Megamullion. (a) Photomicrograph showing occurrence of deformed rock sheet. (b) Video image showing striations parallel to large scale corrugations. (c) Serpentine mylonite. Upper part of the slab is talc schist. (d) Cataclacitic rock of altered basalt. Size of coin is approximately 2 cm.

Magmatic processes under the ridges triggered by water: Experimental constrains

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Recent observations in ophiolites and in the recent oceanic crust showed that hydrous fluids may interact with the just frozen, still very hot lithosphere triggering partial melting processes which may produce distinct late-stage modification or which may even result in the formation of special rock types. In some cases it is evidenced that the water-rich fluids are seawater-derived, thus suggesting a model that hydrothermal circulation at fast-spreading ridge operates much deeper than previously known. Moreover, it has been suggested that this type of hydrothermal circulation at very high temperatures even has the potential to reach the sub-MOHO level causing interaction between seawater and harzburgite at magmatic temperatures. In order to understand the magmatic processes/reactions behind these interactions, we started different series of experiments in specially designed internally heated pressure vessels enabling the control of oxygen fugacity and the rapid quenching of the experimental runs.

(1) Water-saturated partial melting of natural oceanic gabbros between 900 and 1000°C at 200 MPa produces a SiO_2-enriched melt and a characteristic residual paragenesis consisting of An-enriched plagioclase, orthopyroxene and pargasitic amphibole. The experimentally features can also be observed in many typical oceanic gabbros suggesting that the hydrous partial melting of gabbros by hydrothermal activity is a common process within the oceanic crust.

(2) Crystallization experiments in a gabbroic system shows that at pressures > 100 MPa under high water activities olivine and clinopyroxene crystallize first, while the stability of plagioclase is suppressed. This demonstrates that wet MORB-type magmas have the potential to form "wehrlitic" parageneses by the accumulation of early crystallized olivine and clinopyroxene. Thus, typical late wehrlitic intrusions within the oceanic crust (e.g., in the Oman ophiolite) can be regarded as products of hydrous tholeiitic melts.

(3) Water-saturated partial melting of harzburgite at shallow pressures starts at 1060°C leading to melts showing the characteristics of typical "High-Ca boninites". They are highly depleted in incompatible trace elements showing extremely high Ca/Na ratios. A potential fractionation of such melts would lead to highly depleted gabbronorites with An contents of plagioclase generally above 90 mol%. Thus, such cumulates correspond well to those "depleted gabbronorite" sometimes found as late intrusions in the oceanic crust. The residual minerals left behind after the experimental partial melting correspond to typical dunitic assemblages.

Structure of Oceanic Crust and Moho of the Pacific Plate around the Ogasawara Plateau

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To reveal the structure of oceanic crust and Moho near the Ogasawara Plateau, we have analyzed commercial 2D multi-channel seismic reflection data. Oceanic crust and Moho differ significantly north and south of the Plateau. To the north, the structure of oceanic crust is ambiguous and the Moho is discontinuous. To the south, structure within oceanic crust and the Moho is imaged clearly. Moreover, the top of oceanic crust is shallower to the north than to the south. These different characteristics suggest that the Ogasawara Plateau and a fracture zone on the north side of the plateau exert an influence on oceanic crust and the Moho. Magmatism appears to have been vigorous between the plateau and the fracture zone. Differences in acoustic characteristics to the north and south of the plateau are apparent in and illuminated by seismic attributes.

1. Introduction

Knowledge of structure within oceanic crust and Moho geometry is critical for understanding the processes governing the formation and evolution of oceanic crust. Although several models have been proposed for causing reflection Moho—igneous crust (gabbro)-mantle (peridotite) boundary, serpentinization front (Hess model), and other changes in physical properties—the nature of reflection Moho is still ambiguous. Furthermore, interactions between magmatic intrusion accompanying an oceanic plateau (large igneous province, or LIP), 'normal' oceanic crust, and the Moho are poorly known because it is difficult to image and obtain velocity models for such structures within the oceanic lithosphere. The internal structure of oceanic crust has commonly been inferred from velocities determined from wide-angle seismic refraction data. Complementarily, seismic reflection data provide information on geological structure. Furthermore, because seismic reflection data can track reflection Moho laterally, they are critical for siting Integrated Ocean Drilling Program (IODP) drill holes. A dearth of clear reflections within oceanic crust, however, precludes determination of precise stacking velocities necessary for constructing velocity models.

Herein, we use a specific velocity analysis method on multi-channel seismic reflection data which employs the phase of seismic signals, determine a velocity model for oceanic crust, obtain a depth profile by using the velocity model, and interpret the structure of the oceanic crust and the Moho, including enhancement by seismic attributes, around the Ogasawara Plateau (Figure 1).

The Ogasawara Plateau extends to the west of the Marcus-Wake seamount chain in the western Pacific. In map view, it consists of a roughly circular plateau to the west and linear chain of seamounts to the east. The plateau rises 2000 to 3000 m above the adjacent ocean basin floor, and several guyots surmount it. The western part of the Ogasawara Plateau impinges on a convergent plate margin (Izu-Ogasawara Arc at the Ogasawara Trench), and the plateau is subducting or obducting at the Ogasawara Trench (Figure 1). We image the Moho on seismic reflection data from the ~150 Ma Pacific plate around the Ogasawara Plateau.

2. Multi-channel seismic reflection data

In November 2000, the Metal Mining Agency of Japan and the Japan National Oil Corporation (JNOC) acquired multi-channel seismic reflection data in the southern Izu-Bonin Trench region (Figure 1). Seven lines were collected aboard R/V *Geco Emerald.* The sound source consisted of a 134.4 liter airgun array fired every 50 m. The large source array enabled imaging of reflections from the Moho. The receiver array was a 240-channel, 6-km streamer, and the record length was 16 s. In this study, we selected the eastern section of lines D001 and D003, and of the complete Line D00C (line locations in Figure 1), which encompass the Pacific plate (~150 Ma; *Plank et al.,* 2000), including the Ogasawara Plateau. Lines D001 and D00C cross inactive transform fault (fracture zone; gray line in Figure 1).

3. Seismic attributes analysis

Let us assume that the observed seismic trace *f(t)* is the real part of the analytical signal *F(t)*; the imaginary part *g(t)* of the analytic signal can be obtained by Hilbert transformation of the real part *f(t)*. The following equations show these relationships.

$$F(t) = f(t) + i \cdot g(t) = A(t) \cdot e^{i\theta(t)} \qquad (1)$$

$$A(t) = \sqrt{f^2(t) + g^2(t)} \qquad (2)$$

$$\theta(t) = \arctan\big(g(t)/f(t)\big) \qquad (3)$$

The instantaneous phase $\theta(t)$ becomes the argument of the complex trace $F(t)$ (Equation 3), and the modulus $A(t)$ (Equation 2) is called the envelope, or reflection strength, and it represents the total instantaneous energy of the input trace $f(t)$. The instantaneous phase $\theta(t)$ is independent of trace amplitude; thus it relates to the propagation phase of the seismic wave front (*Taner et al.,* 1979). From instantaneous phase (Equation 3), we calculate the "cosine of instantaneous phase $\cos\theta(t)$". Comparing an original seismic trace, its envelope, and the cosine of instantaneous phase reveals that the cosine of instantaneous phase has the same oscillation as the original trace; however, the amplitude becomes one (Figure 2). Therefore, the cosine of instantaneous phase enhances weak reflections and preserves polarity information.

Usually, such seismic attribute analysis is applied to post-stack data; however, we also calculate the cosine of instantaneous phase of the CMP gathers and use them for velocity analysis. *Taner et al.* (1979) proposed use of phase information for velocity analysis. Because the cosine of instantaneous phase diminishes amplitude information, all reflection events have the same amplitude (–1 or 1). Therefore, the velocity spectrum by using the cosine of instantaneous phase CMP gather becomes strong even for low-amplitude events. We applied post-stack migration and depth conversion by using our velocity model.

4. Results

Phase velocity analysis enables us to obtain a velocity model above reflection Moho to the south of the Ogasawara Plateau (Figure 3). Lateral velocity variations in deeper sections may result in part from errors in velocity picking because deep reflections near the Moho do not have sharp peaks in velocity spectra due to small normal moveout (NMO). In contrast to south of the plateau, it is difficult to determine velocities to the north of the plateau because fewer reflections can be observed within the oceanic crust. Therefore, we estimate velocities by constructing seismic profiles with several velocity models (e.g., 5% faster and slower than the initial velocity model) to determine a better velocity model (*Yilmaz,* 2001). We could not determine accurate velocities within the plateau because of its complex, heterogeneous structure. Resolution within oceanic crust (Figure 4) is improved compared to that of a seismic profile using conventional velocity analysis, especially to the south of the Ogasawara Plateau.

5. Discussion

We interpret magmatic intrusions, possibly associated with emplacement of the Ogasawara Plateau, in the central portion of seismic line D003 (arrows in Figure 5) and in the southern portion of line D00C enhanced by an envelope. Because the envelope (Equation 1) ignores phase information, magmatic intrusions can be imaged as blocks on the profile; these intrusions disturb the original structure of oceanic crust. However, magmatic activity to the north of the plateau is more dominant than to the south, because original structure cannot be identified and the top of the oceanic crust is not as smooth. Furthermore, seafloor to the north of the plateau is ~ 1 km shallower than to the south (Figure 1). Moho is observed as a strong and continuous reflection to the south of Ogasawara Plateau, and as discontinuous reflections to the north of the plateau and on the south side of a fracture zone (Figure 4). Differences in characteristics of oceanic crust and Moho likely represent the effects of plateau emplacement. On the north side of the fracture zone (eastern portion of Line D001 & northern end of Line D00C), moreover, oceanic crust seems relatively undeformed and magmatic activity appears to have been low, as to the south of the plateau. Therefore, vigorous magmatic activity, represented by discontinuous Moho reflections, appears to have been sharply constrained by the plateau and the fracture zone.

On both side of the Ogasawara Plateau, furthermore, the depth of Moho deepens proximal to the plateau, which is also consistent with gravity data. The Moho reflection near the plateau is complex; a few reflections can be observed parallel to Moho on the profile enhanced by instantaneous phase (arrows in Figure 6).

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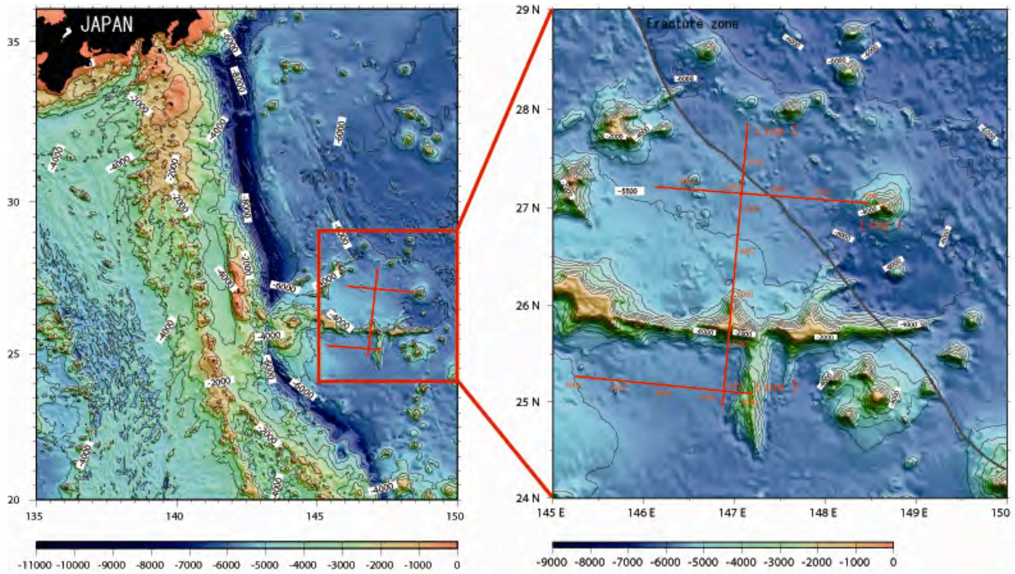
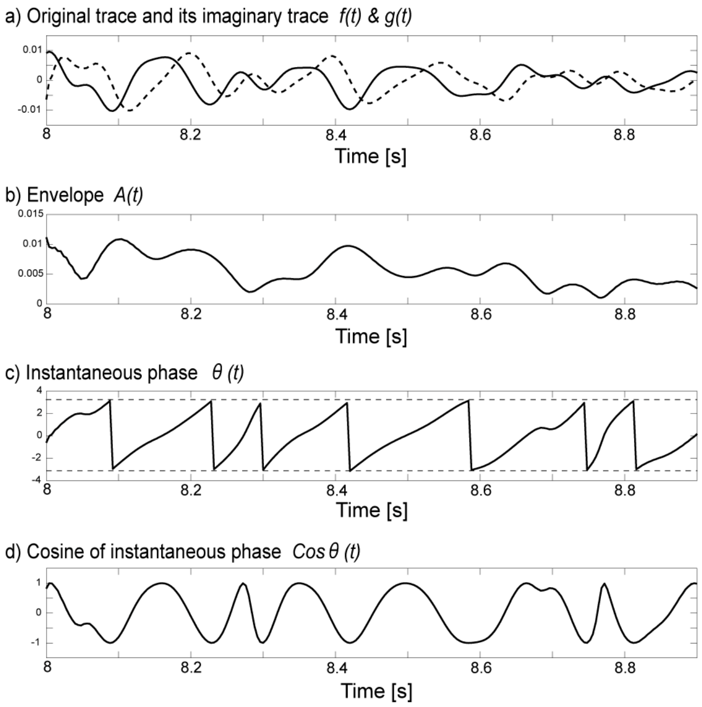


Figure 1. Survey area around the Ogasawara Plateau. Seismic profiles (D001, D003, D00C) are represented by red lines.



a) Original trace and its imaginary trace *f(t)* & *g(t)*

b) Envelope *A(t)*

c) Instantaneous phase *θ (t)*

d) Cosine of instantaneous phase *Cos θ (t)*

Figure 2. Comparison of seismic traces and attributes. (a) Original trace *f(t)* (solid line) and imaginary part *g(t)* (dashed line) of the complex trace, (b) Envelope *A(t),* (c) instantaneous phase $\theta(t)$, and (d) cosine of instantaneous phase $\cos\theta(t)$.

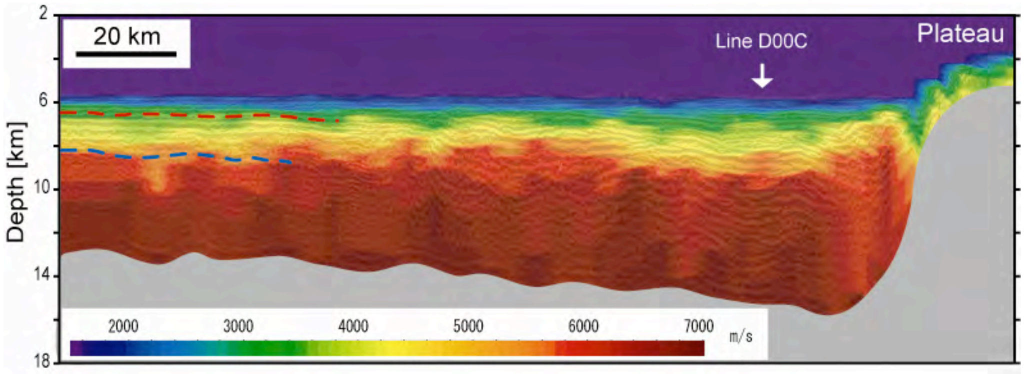


Figure 3. Interval velocity model of Line D003. The gray shaded area corresponds to the mantle (below the Moho reflection). The red dashed line represents the boundary between sediment and layer 2, and the blue dashed line the boundary between layers 2 and 3.

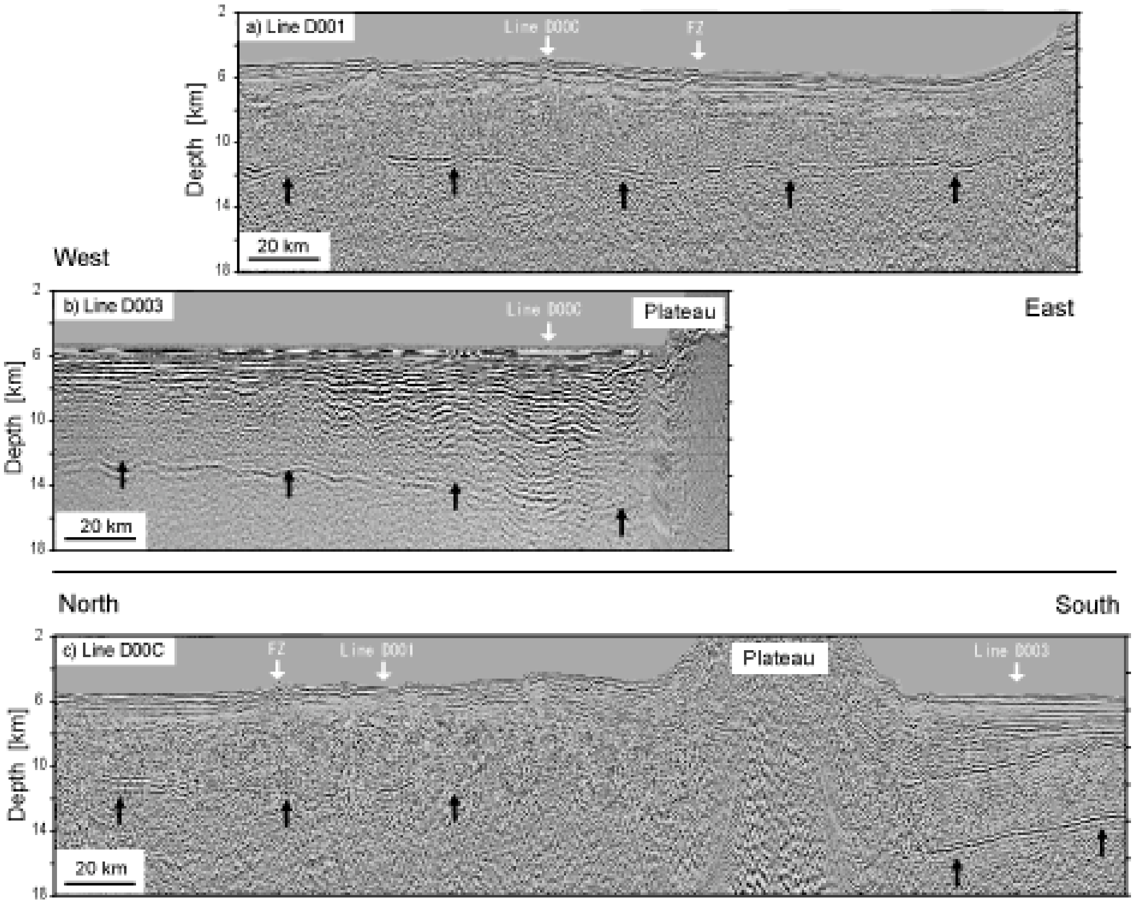


Figure 4. Depth profiles of (a) Line D001, (b) Line D003, and (c) Line D00C. The vertical axis represents depth in km. FZ indicates the location of a fracture zone.

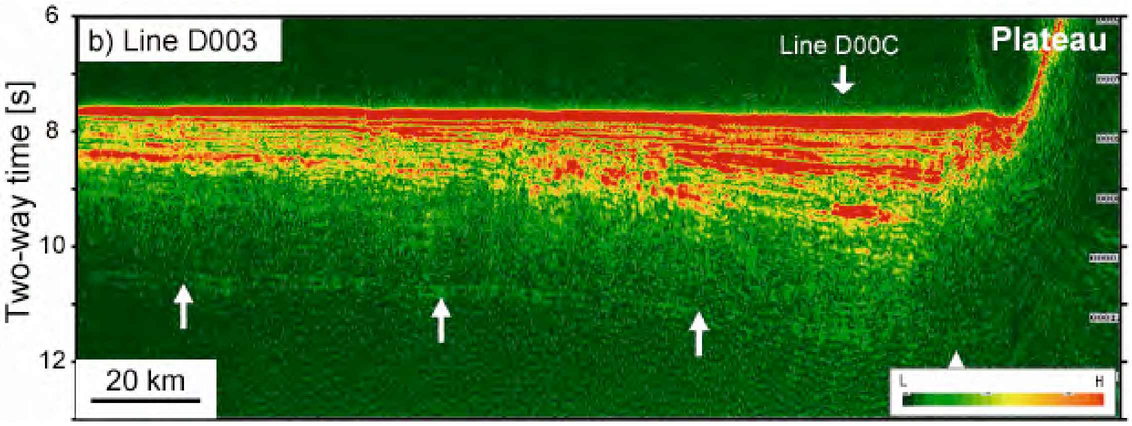


Figure 5. Seismic profile (Line D003) enhanced by an envelope. Red and dark green regions represent high and low values of the envelope, respectively. Magmatic intrusions can be observed in the central to eastern portions of the seismic profile (white arrows).

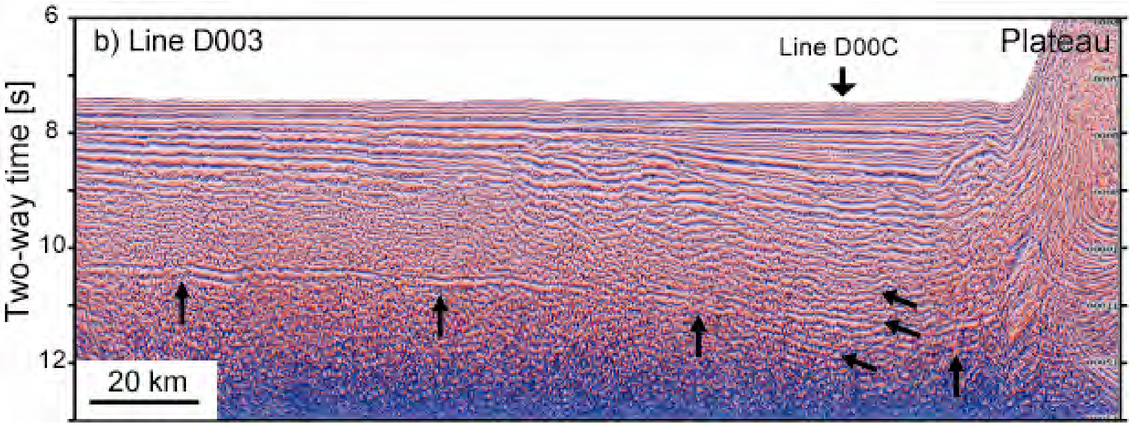


Figure 6. Seismic profile (Line D003) enhanced by instantaneous phase. Red and blue regions represent 180° and –180° of the instantaneous phase, respectively. A few reflections can be observed around the Moho near the plateau (black arrows).

IGNEOUS PETROLOGY OF SITE U1309, IODP EXP. 304/305 AT ATLANTIS MASSIF, MAR 30°N: PRELIMINARY ANALYSIS OF PERIDOTITES

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Introduction and Results of Drilling at Atlantis Massif

Integrated Ocean Drilling Program (IODP) Expeditions (Exp.) 304 and 305 at the Atlantis Massif, Mid-Atlantic Ridge (MAR) 30°N intended to investigate the formation mechanism of oceanic core complexes and evolution of oceanic lithosphere at slow-spreading ridge as well as to document structural and lithological properties of the oceanic lithosphere. A 1.5-2 Myr old oceanic core complex is formed on the inside-corner high at the intersection of Atlantis fracture zone and MAR 30°N (Blackman et al., 2006). The domal, corrugated surface of the massif is interpreted as a long-lived, low-angle normal or detachment fault exposed at the seafloor. High density mantle rocks invoked to explain observed gravity anomalies and high seismic velocities inferred from seismic analysis were expected to occur less than 1 km below the seafloor (e.g., Blackman et al., 2004). Expeditions were operated at two sites: one in the footwall site at and below the detachment fault (Site U1309), and the other in the hanging wall site of an adjacent crustal block (Sites U1310 and U1311). Holes U1309B and U1309D at the footwall site successfully penetrated and recovered a long gabbroic section (Blackmam et al., 2006).

The main hole, Hole U1309D, penetrated 1415.5 meter below the seafloor (mbsf) with an average recovery rate of 74.8%. Over 96% of Hole U1309D is made up of gabbroic lithologies, which comprise amongst the most primitive as well as freshest plutonic rocks known from the ocean floor. The gabbroic rocks are highly variable in grain size and modal composition, and classified into gabbro, gabbronorite, olivine gabbro, troctolite, "olivine-rich troctolite" and oxide gabbro. Serpentinized peridotites, on the other hand, constitute only 0.3% of the drill core. Diabase and basalt crosscutting the gabbroic sections comprise 2.9%. Medium-grained to pegmatitic gabbros and gabbronorites, including minor amount of olivine and Fe-Ti oxides and/or orthopyroxene, comprise the most abundant rock type in the gabbroic rocks (55.7%). The oxide gabbro which contains Fe-Ti oxides of more than 2 vol.% and rarely exceeding 10 vol.% makes up 7.0% of the Hole U1309D. Olivine gabbro is the second most abundant rock type (25.5%) that contains wide ranges of modal olivine (10 to 50 vol.%). The olivine gabbro locally grades into troctolitic gabbro and troctolite. More olivine-abundant troctolite (>70 vol.% modal olivine), "olivine-rich troctolite", was recovered 5.4% including thicker intervals between 312 and 344 mbsf, and 1092-1236 mbsf. It has a cumulate-like texture with subhedral to rounded olivine and interstitial to poikilitic plagioclase and clinopyroxene in variable proportions. On the other hand, Hole U1309B penetrated 101.8 mbsf with an average recovery rate of 46%. Gabbroic rocks, peridotite and basalt/diabase constitute 49%, 3% and 48% of the core recovered, respectively. Hole U1309B is characterized by two intrusive series separated by a narrow interval (~2-4 m) of relatively undeformed serpentinized harzburgite. The upper sequence comprises basalt, diabase and gabbro, and the lower sequence consists of diabase and gabbro.

Serpentinized peridotites were recovered from both Holes U1309B and U1309D (Blackman et al., 2006). Harzburgite intervals were collected at 58 mbsf in Hole U1309B. The harzburgites exhibit protogranular texture with alteration minerals ranging from 60 to 99% in volume. The harzburgite interval is in direct contact with the coarse-grained gabbro above and the lower boundary was not recovered. Several peridotite intervals were described at different depths of shallower zones, between 61 and 224 mbsf, in Hole U1309D. Their compositions range from lherzolite to dunite. The degree of alteration varies from 10% to 100%, and dunites are the most severely altered. All peridotites show evidence for intensive impregnation of melts, such as interstitial plagioclase, scattered melt-derived clinopyroxenes and olivine chadacrysts in coarse clinopyroxene oikocrysts. For whole-rock compositions of the peridotite, Mg# and Ni content are relatively high and limited, such as ranging from 87.2 to 90.7, and from 1200 to 3000 ppm, respectively.

In this report, we present preliminary data in mineralogy and geochemistry of the peridotite samples from Holes U1309B and U1309D.

Petrology of Peridotites from Atlantis Massif

Studied samples are from intervals at 58 mbsf in Hole U1309B (Core 304-1309B-11R), and at 61, 132, 155, 172 and 314 mbsf in Hole U1309D (Cores 304-1309D-10R, 304-1309D-23R, 304-1309D-27R, 304-1309D-31R and 304-1309D-61R, respectively). Detail of sample intervals and their modal compositions are shown in Table 1. The harzburgites from Hole U1309B (Hole B harzburgites) are free from plagioclase and contain ~2.5 vol.% of clinopyroxene. Small concentrations of chromian spinel with amphibole inclusions were observed in an interval (Sample 1309B-11R-1, 95-98 cm). The samples from Hole U1309D are wehrlite to lherzolite with various modal amounts of plagioclase (1-13 vol.%) (Hole D samples). Only orthopyroxene is completely altered in the lherzolite (Sample 1309D-10R-1, 91-107 cm) although olivine and clinopyroxene are relatively free from alteration.

Major- and minor-element compositions of minerals were determined by electron microprobe analysis at Kanazawa University (e.g., Tamura and Arai, 2006). Mg# [Mg/(Mg+Fe^{2+}) atomic ratio] and Cr# [=Cr/(Cr+Al) atomic ratio] of chromian spinel in all samples are relatively constant, ranging from 0.42 to 0.67 and from 0.50 to 0.58, respectively (Fig. 1a). TiO_2 contents of chromian spinel in Hole B harzburgites are generally less than 0.4 wt%. Chromian spinels in the Hole D samples, on the other hand, have a wider range of TiO_2 contents (0.3-3.0 wt%). Forsterite contents (Fo) of olivine vary from 89.7 to 91.0 and from 86.5 to 90.7 in Hole B harzburgites and the Hole D samples, respectively (Fig. 1b). Mg# of clinopyroxenes varies from 0.884 to 0.925 whereas Al_2O_3 contents are constant (3-4 wt%). Mg# of clinopyroxenes in one of Hole B harzburgites (Sample 304-1309D-11R-2, 0-8 cm) tends to be correlated with grain size (see Fig. 2a). Compositional relationships between olivine and chromian spinel are shown in Figure 1b. The Hole B harzburgites are plotted within OSMA (= olivine-spinel mantle array; Arai, 1994). Most of the Hole D samples are plotted off OSMA (Fig. 1b).

For one Hole B harzburgite (Sample 304-1309D-11R-2, 0-8 cm) and 6 samples from Hole U1309D, trace-element compositions (REE: Rare earth elements, Ti, Sr, Y and Zr) of clinopyroxenes were determined by LA-ICP-MS at Kanazawa University (e.g., Ishida et al., 2004; Tamura and Arai, 2006). Chondrite-normalized trace-element patterns of clinopyroxenes are shown in Figure 2. Clinopyroxenes in Hole B harzburgite show considerably wide intra-grain and inter-grain trace-element heterogeneity, in terms of intra-grain and inter-grain. The compositional differences between clinopyroxene grains tend to be dependent on grain size. The chondrite-normalized REE patterns are spoon- to flat-shaped with relatively low heavy-REE (HREE) abundances (e.g., $Yb_{N=\text{chondrite-normalized}}$

$_{\text{value}}$ = 2.1-4.2) (Fig. 2a). The coarse clinopyroxene grains (e.g., Nd_N = - 0.67, Ce_N = 0.13-1.08) is more depleted in middle-REE (MREE) and light-REE (LREE) than fine ones (e.g., Nd_N = 0.79-3.77, Ce_N = 1.47-3.61). Each clinopyroxene grain has compositional zoning in which REE abundances are systematically higher in rim than in core. The REE patterns of clinopyroxene rim show negative Eu anomaly although coarse grain rim is similar in other REE abundances to fine grain core. Most of clinopyroxene trace-element patterns exhibit negative anomalies in Ti, Zr and Sr relative to REE. The clinopyroxene rim shows stronger negative anomaly in Sr, compared to the core (Fig. 2a). The REE patterns of clinopyroxenes in Hole D samples show gentle slope from HREE to LREE with wide range of REE abundances [e.g., Yb_N = 5.95-17.94, Ce_N= 0.98-7.72, $(Ce/Yb)_N$ = 0.16-0.42] and negative Eu anomaly. Most of clinopyroxenes show various degrees of negative anomalies in Ti, Zr and Sr. However, clinopyroxenes with higher REE abundances (Sample 304-1309D-10R-1, 91-107 cm) exhibit positive Zr anomaly relative to REE (Fig. 2b). Hole D samples are comparable in clinopyroxene trace-element compositions to olivine gabbros from the MARK area (Coogan et al., 2000) (Fig.. 2b).

Based on the modal composition and mineral chemistry, the Hole B harzburgites are possibly residual materials of upper mantle origin. Cr# of chromian spinel primarily indicates that the degree of partial melting is close to the upper limit of melting degree of abyssal peridotites (Fig. 1b). The HREE abundances and steep REE pattern from HREE to MREE of coarse-grained clinopyroxene core in Hole B harzburgite are concordant with such a high melting degree (Fig. 2a). However, the LREE-enriched trace-element patterns of clinopyroxenes cannot be explained by REE fractionation during simple partial melting. Petrological and geochemical features of Hole D samples are different from those of Hole B harzburgite. Mineral chemistries (Figs. 1 and 2) primarily indicate that Hole D samples are of cumulus origin rather than simple residue. However, textural characteristics suggest the Hole D peridotite were formed by more complicated processes, such as melt impregnation (Blackman et al., 2006). The origin of Hole D peridotites, therefore, is still controversial. Further studies of the genetic relationships between them must contribute to understanding of magmatic processes at the mid-ocean ridges and the oceanic core complex formation.

Table. 1. Modal compositions of studied samples from Site U1309.

Core-Section	Interval (cm)	OL	OPX	CPX	SP	PLG	*D-alt*
304-1309B-							
11R-1,	95-98	82	14	2.0	2.0	-	*65%*
11R-1,	95-99	87	12	-	1.1	-	*60%*
11R-1,	100-104	79	20	0.2	0.4	-	*77%*
11R-1,	114-119	83	15	1.8	0.4	-	*87%*
11R-2,	0-8	78	20	1.0	1.0	-	*86%*
11R-2,	23-30	77	20	2.5	0.7	-	*85%*
304-1309D-							
10R-1,	91-107	76	17	5.2	0.5	1.0	*24%*
23R-2,	8-13	89	-	8.1	0.9	2.0	*49%*
27R-3,	0-4	84	11	7.2	0.5	0.8	*88%*
31R-2,	20-22	81	17*		0.7	1.6	*100%*
61R-1,	22-26	75	-	11	0.2	13	*62%*
61R-1,	47-52	81	-	10	1.2	8.7	*65%*

Notes: Proportions (vol.%) of primary phases for olivine (OL), orthopyroxene (OPX), clinopyroxene (CPX), spinel (SP) and plagioclase (PLG). Recalculated pseudomorphs as each primary phase. *D-alt:* Degree of alteration estimated from olivine and pyroxene alterations. *as pyroxene modal ratio due to severe alteration.

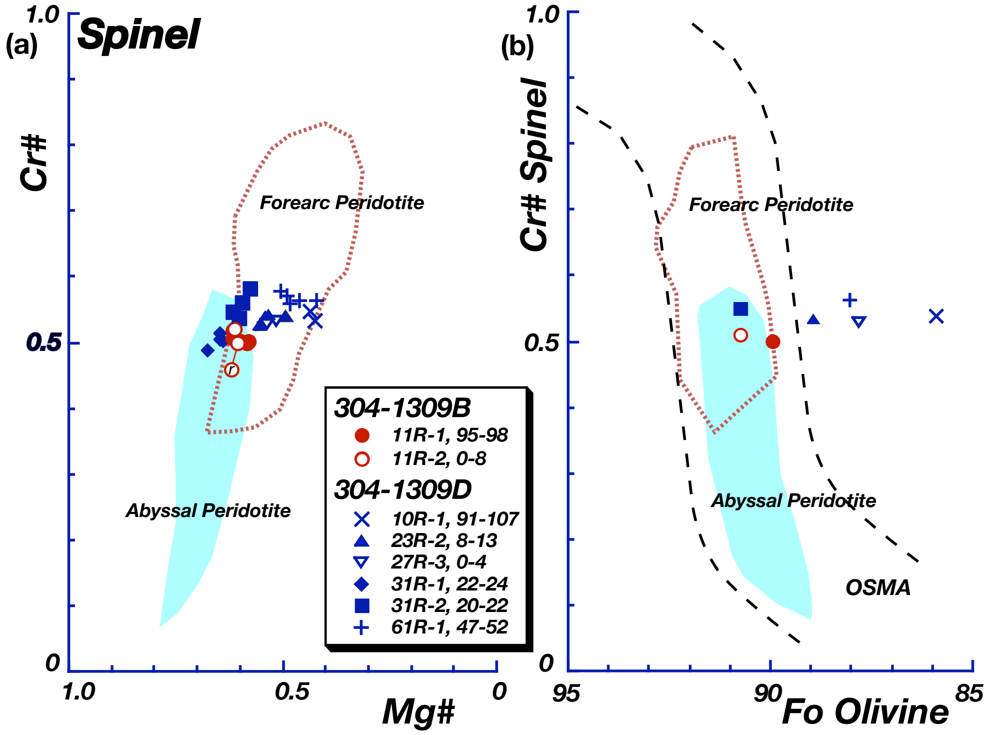

Figure 1. (a) Mg# [=Mg/(Mg+Fe^{2+})] vs Cr# [=Cr/(Cr+Al)] of chromian spinel. (b) Relationships between forsterite content (Fo) of olivine and Cr# of chromian spinel. OSMA: olivine-spinel mantle array, a spinel peridotite restite trend (Arai, 1994). Abyssal peridotite field from Dick and Bullen (1984) and Arai (1994). Forearc peridotite field from Bloomer and Hawkins (1983), Bloomer and Fisher (1987), Ishii et al. (1992) and Parkinson and Pearce (1998).

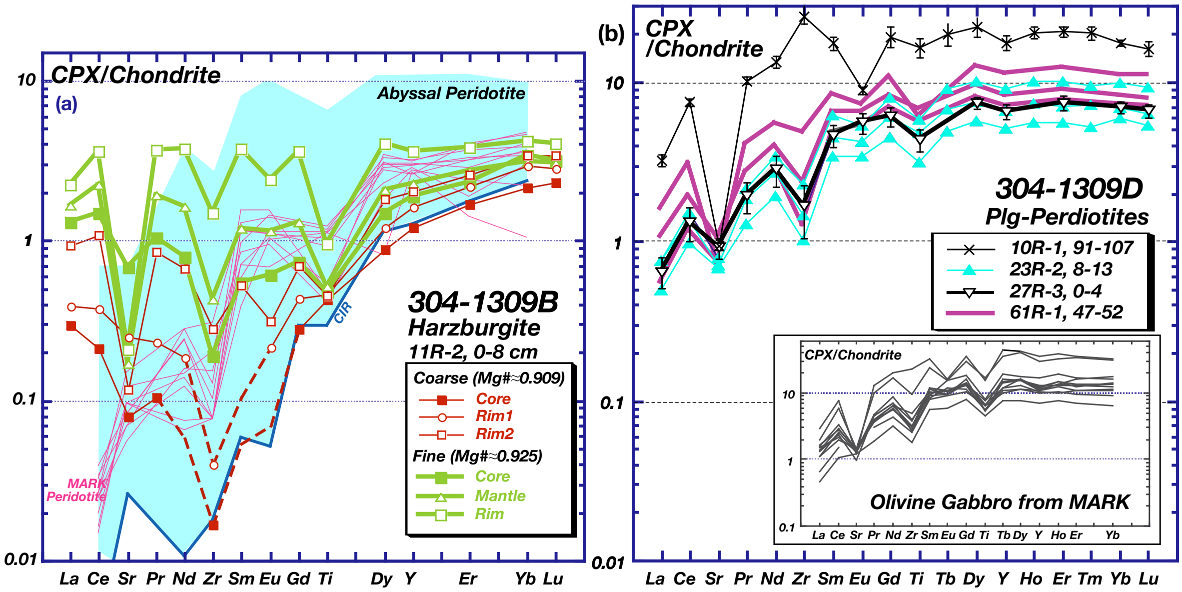

Figure 2. Chondrite-normalized trace-element patterns of clinopyroxene in peridotites from Hole B (a) and Hole D (b). Analyzed by LA-ICP-MS (50-70 µm in spot diameter) at Kanazawa University (Ishida et al., 2004; Tamura and Arai , 2006). Chondrite values from Sun and McDonough (1989). Abyssal peridotite field from Johnson et al. (1990) and Hellebrand et al. (2002). Lower limit of the abyssal peridotite field was defined by clinopyroxene compositions of the peridotite from the Central Indian ridge (CIR) (Hellebrand et al., 2002). For trace-element compositions of MARK (Mid-Atlantic Ridge Kane Fracture Zone), peridotite and gabbro data are from Ross and Elthon (1997) and Coogan et al. (2000), respectively.

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Oceanic Core Complexes and Crustal Accretion at Slow-Spreading Ridges. Indications From IODP Expeditions 304-305 and Previous Ocean Drilling Results

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Oceanic core complexes expose intrusive crustal rocks on the seafloor via detachment faulting and are often associated with significant extents of serpentinized mantle peridotite at the seafloor. These serpentinite units have unknown thickness in most cases. Assuming that steep slopes surrounding the domal core provide a cross section, one would infer they comprise much of the section for depths of at least several hundred meters.

IODP expeditions 304-305 results at the Mid-Atlantic Ridge 30°N (Atlantis Massif), taken together with recent results from seafloor mapping and ODP drilling in the Atlantic as well as on the SWIR, suggest that a revised model of oceanic core complex (OCC) development should be considered. All of the ODP/IODP drilling at 4 different core complexes and/or inside corner highs so far have recovered only gabbroic sections, with almost no serpentinized peridotite.

To account for this observation we propose a revised model for oceanic core complex development based upon consideration of the rheological differences between gabbro and serpentinized peridotite: emplacement of a large intrusive gabbro body into a predominantly peridotite host is followed by localization of strain around the margins of the pluton, eventually resulting in an uplifted gabbroic core surrounded by deformed serpentinite. The development of a detachment fault system on the central dome of

Atlantis massif may have occurred relatively late in its evolution, controlling the exposure along a domal high via mostly brittle faulting.

This working model is different from previous published models in that OCC represent the tectonic and morphologic expression of the magma-rich end-member of a fundamental mode of crustal accretion- the intrusion of gabbro plutons at depth. The model resembles a system of ball-bearings, in which episodically some gabbroic "balls" are larger. It does not necessarily imply that the detachment fault capping OCC is a single, deep-rooting fault. The geometry of the fault system may vary on a case-by-case basis, depending on the volume of gabbro present beneath the axis and on its crystallization depth. The model implies that serpentinized fault zones envelop the gabbro bodies, thus explaining the paradox of dominantly gabbroic cores in the vicinity of seafloor serpentinites on top or on the flanks of OCC. We predict that serpentinites on the southern wall of the Atlantis Massif may represent the serpentinite matrix of the crust south of the termination of the dominantly gabbroic core. Further drilling on the southern ridge is required to determine where the peridotite/gabbro boundary is since current data are equivocal.

White Papers

- 21st –Century Mohole as a multi-disciplinary science
  S. Arai, N. Abe, and Y. Tatsumi

- White paper from S.P. ingle

- Oman Ophiolite Drilling Project Preliminary Proposal
  P.B. Kelemen, B. Ildefonse, P.A. Pezard, A. Nicolas, H. Al Azri, C.J. MacLeod, R.S. Detrick, K.M. Gillis, S. Umino, C. Langmuir, S. Constable, and D.A.H. Teagle

- White paper from Y. Ohara

- Drilling to the Moho with IODP: lessons from the past and the need for Interactive Drilling Operations
  P.A. Pezard, B. Ildefonse, and V. Maury

- White paper from J. Sinton

21st –Century Mohole as a multi-disciplinary science

S. Arai, N. Abe, and Y. Tatsumi

Mohole has two issues: one is to obtain whole crustal section as a continuous drill core and the other is to drill through in-situ Moho. Both will provide us with innovative information if we prepare well. “Nature of Moho” is a key to Mohole, and we should select the site for Mohole where we can resolve the question “What is the oceanic Moho?”

(1) What is Moho?

Moho is a discontinuity of Vp between around 7 km/sec above and around 8 km/sec below, being considered most typically as gabbro/peridotite boundaries. For example, we can obtain both peridotite/pyroxenite and mafic granulite xenoliths in volcanics from continental or arc regions; the former and the latter are probably derived from the upper mantle and lower crust, respectively. Observations from ophiolites and limited exposures from the ocean floor suggest that boundaries between peridotites and layered gabbros correspond to oceanic Moho.

Moho is changeable along with modification of rock properties during geological processes. Active igneous activity continuously changes the deep parts of some arcs like the Japan arcs, where Moho has been changing as well due to addition of new cumulates and restites and subtraction of materials by delamination. Cooling of hot plutonic rocks may promote a reaction, olivine + plagioclase = pyroxenes + spinel (troctolitic gabbros to spinel pyroxenites), may cause upward transformation of Moho. Selective hydration and fracturing of the uppermost mantle may change its properties to be crust-like, resulting in Moho modification.

(2) Nature of the oceanic Moho

The oceanic Moho may be variable depending on structure of the oceanic lithosphere, which is variable depending both on spreading rate and on distance from ridge-axis discontinuities. The oceanic lithosphere is composed of mafic igneous rocks, peridotites and their alteration products. Formation of the oceanic Moho is dependent on distribution of mafic and ultramafic rocks, thermal structure and degree of water circulation. If the Hess Model is applicable, the lowermost crust should be antigorite serpentinite. If the seismic discontinuity is a front of water circulation at lower temperatures (<500 to 600°C, lower than antigorite stability limit), chrysotile/lizardite serpentinite is possible as lower crust materials. Anyway, nature of the oceanic Moho has never been well correlated between petrologic and seismic properties.

(3) Role of ophiolite

Ultra-deep drilling will be almost one-dimensional even though it is highly penetrative through the Moho, and we cannot examine the variety of Moho, if any. This will be partly overcome by using results of studies on well-exposed ophiolites like the Oman ophiolite. There are at least two kinds of Moho in Oman: “gabbro-in-dunite” Moho and “dunite-in-gabbro” Moho. The former is characterized by gradual change from underlying dunite (Moho-transition zone dunite) to layered gabbro with an upward increase of frequency of gabbro bands (sill-like intrusions) in the dunite. This may have been formed at a spreading ridge and is primary. The latter is characterized by a secondary gabbro/dunite contact, which was made by intrusion of dunite (late-intrusive dunite) to gabbro. Nature of the late-intrusive dunite is problematic: if it is a mid-ocean ridge product, we can expect two kinds of Moho from the present-day ocean floor. If it is of arc origin, we should examine only the “gabbro-in-dunite” Moho for probing oceanic lithosphere. Ophiolite is useful as an analogue of oceanic lithosphere, but care should be taken when combined with Mohole.

(4) Characterization of oceanic crust

In addition of igneous activity to produce the initial oceanic lithosphere at spreading ridges, secondary modification (deformation and metamorphism/alteration) of rocks constituting the oceanic crust is important to understand Earth’s system. Problem concerning circulation of hydrothermal solution and related modification of oceanic lithosphere has not been fully understood and is definitely one of the issues only addressed by Mohole. We are interested in way and depth of hydration and relevant chemical budget, which may constrain physical and chemical properties of oceanic lithosphere. This is highly relevant to properties of slab and mantle wedge and mantle dynamics in deeper mantle. The hydrothermal circulation can extend serpentinization front downward into the peridotitic portion if mafic crust is thin enough and thermal regime permits. This may produce the oceanic crust of Hess Model. This can be testified by ultra-deep drilling into gabbroic bodies exposed in the ocean floor (e.g., Atlantis Bank). It is a type of Mohole.

(5) Deep biosphere

Depth extent of biosphere in the oceanic lithosphere may be closely related with the hydrothermal circulation. This is also one of the important issues of Mohole.

(6) Strategy

1. Pre-Mohole on the Oman ophiolite

We would like to propose to systematically determine physical properties of rocks that are altered to various extents and are mixed with varying proportions. It will facilitate our construction of petrologic model using physical (seismic) properties of oceanic lithosphere. This is indispensable to successful preparation for and operation of Mohole. The Oman ophiolite is a good target for such a Pre-Mohole. We can also conduct seismic experiments to determine velocity structure of the ophiolite, where surface geology has been well known. They will be combined with continental drilling.

2. IBM (Izu-Bonin-Mariana arc) seismic surveys

Detailed seismic structure has been determined in IBM by a JAMSTEC group. Combined with a petrologic model of IBM crust-mantle formation, we can establish nature and origin of Moho at an oceanic island arc.

3. Mohole at <2,500 m water depth

For the first phase of Mohole, we propose drilling on Lau Basin, one of the backarc basins. The Sea of Japan, which is composed of an ocean basin and rifted/stretched continental lithosphere and can provide us with unrivaled information, is also a candidate for this Mohole.

4. Mohole at 4,000 m water depth

For the second phase of Mohole, some place can be selected at the equatorial EPR, where active and fossil spreading ridges are available. Drilling on the ocean lithosphere of fast-spreading ridge origin is unparalleled as a “standard oceanic curst-mantle”.

5. Toward comprehensive understanding of Moho

If we can accomplish a series of project proposed here, we proceed to comprehensively understanding Moho, the shallowest important discontinuity of the Earth, at various tectonic settings.

Statement of Interest

Mission Moho: Understanding the Formation and Evolution of the Oceanic Lithosphere
6 – 9 September, 2006 Portland, Oregon
28 April, 2006

Stephanie P. Ingle
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Title:
Scientific Objective: To understand the mantle dynamics and magmatic processes that lead to the production of oceanic lithosphere.

Importance:
The study of ridge magmatic processes is the IODP objective toward which we have made the least progress. The next phase of ocean drilling should attempt to bring our knowledge of these processes in line with our understanding of comparably broad initiatives in the IODP long-term plan. Basic understanding of oceanic lithosphere comes from the study of ophiolites, but their comparability to normal ocean lithosphere remains unknown. Comparison of different layers of the oceanic lithosphere formed at typical mid-ocean ridges will greatly improve our understanding of this important endmember in crustal production. Of utmost importance include: 1) the investigation of along- and across-axis geochemical variation, determinable by several shallow drill holes in zero-age oceanic crust (which poses distinct technological challenges), and 2) the architecture and chemical interrelationships of a complete drill section through the entire oceanic crust and into the uppermost mantle (again, at present limited due to technology). The absence of existing technologic remedies to these problems should not, however, deter us from planning to accomplish these objectives in the here and now. These technological challenges are likely to be overcome in the near future and waiting until after that point is reached to begin planning is not necessarily the prudent course.

Necessity for Drilling:
1) In order to understand geochemical variation along- and across-axis requires drilling for two primary reasons. Slightly off-axis rocks are sometimes not accessible by ROV or submersible sampling, and dredging has extreme spatial resolution problems. For these reasons, drilling is required to accomplish this objective, for maintaining excellent spatial resolution, and for allowing for clear comparisons to pre-existing geophysical images. 2) In order to understand how the oceanic lithosphere forms requires examination of the upper mantle, the mantle – crust transition, and the gabbros, dikes and lavas of the crust within a single location. This type of comparison cannot be accomplished by dredging or even by submersible or ROV sampling, as complete lithosphere exposures are not present at any single locale, and because the chemical interrelationships cannot be examined due to lack of stratigraphic control.

Oman Ophiolite Drilling Project
Preliminary Proposal

Proponents:
Peter B. Kelemen[1], Benoit Ildefonse[2],
Philippe A. Pezard[2], Adolphe Nicolas[2], Hilal Al Azri[3],
Chris MacLeod[4], Robert S. Detrick[1], Kathryn M. Gillis[5],
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January 12, 2001; updated April & August, 2006

Note added by Peter Kelemen in April, 2006:

This preliminary proposal, first submitted in 1998, received approval by the ICDP in 2001, and we were offered funding for a workshop to be held in Oman. However, then came September 11, 2001, and after that, frankly, the proponents have been too busy with other projects (in Kelemen's case, ODP Leg 209 and the Talkeetna Arc Continental Dynamics Project) to do this one justice, and so we have postponed it.

If I were going to update this more thoroughly now, I would add quite a bit on hydrothermal alteration. As igneous petrologists, we used to be careful not to sample altered rock. This was short sighted. I am inspired by the recent work by Bosch et al. (J. Petrol 04) and related papers by Francoise Boudier, Dave Mainprice and Adolphe Nicolas on alteration veins in the Oman lower crust. In the mantle section, I think it should be a priority for all of us to study the kinetics of serpentinization and carbonation of peridotite, since these reactions may be the best hope for large scale, rapid carbon sequestration. Both Margot

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Introduction

This is a revised version of an informal planning letter initially submitted to the ICDP by this group in 1997. After receiving a letter from the ICDP encouraging us to prepare a full proposal, we decided to prepare a Preliminary Proposal instead. Our wish was to clarify our intentions and to ensure that the full proposal, when it is submitted, has the best possible chance of acceptance by the ICDP. At this point, SAG decided to turn down our Preliminary Proposal. Now determined to proceed with this project, we recognize that developing it outside ICDP would not be logical.

With this Preliminary Proposal, as in 1998, we are specifically requesting funds for a workshop to assist in developing a full proposal. The cost, for travel and lodging, would be approximately $ 30,000.

Formation of igneous crust at oceanic spreading centers is the most voluminous and simplest igneous process on Earth. Increasing understanding of this process has led to major advances in general theories of partial melting , melt transport, heat transfer from the mantle to the hydrosphere, crustal genesis, and hydrothermal systems. Study of the Oman ophiolite has been an integral part of this progress. After landmark research by an international group in the late 1970's and 1980's (e.g., summaries by Coleman & Hopson 1981; Lippard et al. 1986; Nicolas 1989), recent work has provided vital, first order results on **mechanisms of melt extraction from the mantle beneath ridges** (Nicolas 1986, 1990; Ceuleneer & Rabinowicz 1992; Leblanc & Ceuleneer 1992; Ildefonse et al. 1993; Nicolas et al. 1994a,b; Kelemen et al. 1995b, 1997b; Ceuleneer et al. 1996; Benoit et al. 1996), on **the geometry and nature of mantle upwelling** (Nicolas & Rabinowicz 1984; Rabinowicz et al. 1984; Ceuleneer et al. 1988; Ceuleneer 1991; Nicolas & Boudier 1995; Ceuleneer et al. 1996), on the kinematics and processes of **igneous accretion of the Moho transition zone and lower oceanic crust** (Nicolas et al., 1988; Benn et al., 1988; Ildefonse et al. 1993; Nicolas et al. 1994a; Boudier & Nicolas 1995; Boudier et al. 1996; Kelemen et al. 1997a; Korenaga & Kelemen 1997,1998), and on the nature of the **transition between upper gabbros and overlying, sheeted dikes** (Rothery 1983; Nicolas & Boudier 1991; MacLeod & Rothery 1992).

Although some of these results are uncertain and are the topic of continuing discussion (e.g., Nicolas 1994; Phipps Morgan 1995; Kelemen et al. 1997b), there can be no doubt that work based in Oman has played a vital role in developing crucial paradigms for understanding oceanic spreading ridges, and for catalyzing continued research on both active ridges and ophiolites. Recent m-scale resolution transects in the field to study the temporal variability of accretion processes (Pezard et al. 2000) have demonstrated the importance of high resolution studies. Hypotheses based on field observations in Oman, and discrepancies between these hypotheses, have clearly delineated the need for additional data to resolve some fundamental problems. The additional data that are required may be separated into two complementary types.

(1) Systematic study of complete sections of the ophiolite, with emphasis on crucial boundaries at the dike/gabbro and crust/mantle interfaces, are required to provide statistically sound characterization of features including the proportions of rock types and the orientation of specific structural indicators.

Measurements to be made on core would be technically similar to those made in the field and on specimens recovered from outcrop. However, emphasis would be on obtaining a large number of analyses from a nearly continuous sample, in order to determine size/frequency characteristics, average values, and variances, on many length scales. Also, it is likely that mantle samples recovered from below the weathering horizon will be much less altered than those available from outcrops.

(2) Characterization of physical properties of the same sections of the ophiolite is needed to refine techniques used in the modern oceans, especially those used to infer the nature of seismic reflectors.

While the physical properties of rocks exposed within 1 to 2 km of the surface in the ophiolite may be quite different from the properties of similar rock types at greater depth in the modern oceans, drilling and geophysical logging can nonetheless provide quantitative constraints on seismic response, density, and conductivity of appropriate rock types with known crack density, alteration, and depth. Geophysical drillhole logs also provide a vital link between micron to cm scale measurements on core samples, and 100 m to 10 km scale geophysical observations at sea.

Specific examples of data needed to test central hypotheses are given in a later section.

Research methods

We propose a multi-disciplinary, diamond drilling program. Using diamond coring techniques that are standard in the mineral exploration industry, we will drill a series of 500 to 1000 meter holes which together comprise a full crustal section through the ophiolite. In preparing a preliminary estimate of costs, we have limited the estimated depth to 1 km for each hole because drilling often becomes difficult below this depth, and shorter holes do not provide an optimal cost/benefit ratio because of the large, fixed costs of setting up a diamond drill rig at a specific site.

During the drilling project, we will try to optimize the depth of each hole in terms of cost per foot. Also, to minimize cost, the expected size of boreholes will be down to 100 mm (4"). Finally, we will make the proposed drill holes in a stepwise fashion, with funding for later holes contingent on successful results, in both scientific and logistical terms, from initial holes.

It will be quite expensive to drill a full crustal section from the ophiolite. Initially, drilling will be conducted through on crucial petrologic and geophysical boundaries between the crust and the upper mantle, and between dikes and gabbro. Pending successful results from these holes, additional holes will be drilled to complete a full section, and to evaluate the spatial variability along crucial horizons by acquiring cores from two different sections.

An international consortium of scientists will analyze the core to establish a systematic set of data on rock composition, structure, and physical properties, and will conduct downhole geophysical experiments to investigate magnetic, seismic and resistivity properties of the lithologic types in the ophiolite. At this stage, the planning group is limited to Adolphe Nicolas, Philippe Pezard and Benoit Ildefonse (Montpellier, France), Hilal Al Azri (Muscat, Oman), Chris MacLeod (Cardiff, UK), Damon Teagle (Southampton, UK), Kathryn Gillis (Victoria, Canada), Susumu Umino (Shizuoka, Japan), Nikolas Christensen (Wisconsin, USA), Charles Langmuir (New York, USA), Steven Constable (Scripps IO, USA), Eric Humler (Paris, France), Bob Detrick and Peter Kelemen (Woods Hole, USA). However, we anticipate that this project will be very attractive to a wide range of geoscientists. Once the general drilling plan is complete, we will seek funding for a scientific planning meeting, advertised in international journals, and try to involve a wide and representative group from the ocean and earth sciences communities in determining the best possible analytical program. In this and many other regards, we wish to adopt the successful Hawaiian Drilling Project as an example to be followed.

Downhole logging will provide a key element in linking micron to centimeter scale observations of samples from drill core to 100 m to 10 km scale geophysical observations of active ocean ridges. The most important physical properties to be measured by downhole logging are acoustic velocities (Vp and Vs), for comparison to seismic velocity measurements on samples of drill core, and seismic studies of the ocean crust. Such measurements are recorded in boreholes at acoustic frequencies (a few tens of kHz), then compared to differential transit times from vertical seismic profiles. Electrical resistivity, magnetic susceptibility and density, as well as high resolution borehole wall images are also key measurements for the determination of bulk crustal properties. For example, we hope to use petrographic study of the core to learn how geophysical logs record information on igneous layering in gabbroic rocks, yielding a continuous record of layer spacing from the geophysical logs even where core is not recovered.

Because the holes will be as narrow as 100 mm, downhole measurements will be done using slimline sensors. Except for FMS-like electrical images, all standard measurements are available from sensors with diameters between 50 and 75 mm (2 and 3"). Besides seismic experiments, the main objectives of the downhole measurement program will be to provide continuous quantitative measurements and images in order to perform structural and lithological studies, and to obtain measurements of standard physical properties. To detect altered horizons, or to analyze variations in magma composition, spectral analyses of the natural radioactivity of the rock (yielding continuous profiles of K, Th, and U), and magnetic susceptibility measurements (for the detection of titanium and iron-rich oxides) will also be important. At a larger scale (m to 10's of m), downhole seismic experiments or ground penetrating radar measurements, for example, might be made to evaluate the lateral continuity of features identified in the core and from logging. Surface to borehole methods may then be used to link the borehole data to the surrounding geology, and to integrate downhole measurements at seismic scale.

Scientific funding will be sought concurrently with funding for drilling (e.g., from the US National Science Foundation and the French "Centre National de la Recherche Scientifique"). In addition to downhole geophysical logs collected during the drilling process, it will be essential to make a very large number of physical, chemical and structural measurements on drill core. This analytical program will be carried out as a service with drilling, perhaps in part by commercial labs, to provide a set of basic data similar to that collected by the Shipboard party during ODP drilling programs. In this way, the proposed project will be different from typical geochemical or structural studies where measurements are made to address specific research objectives. Such a basic data gathering function will be essential to the success of the project, and must be supported by special grants.

In order to ensure long term availability of core to an international group of research scientists, diamond drill core will be archived permanently in a new facility, which we hope can be built in Oman. Once the core has been logged and archived, the international scientific community will be encouraged to develop specific research projects to study it. Interested scientists will apply, and the sample distribution policy will be to provide material, for the cost of shipment, upon approval by a scientific steering committee for the first 5 years after the core is obtained. Where possible, core will be cut lengthwise into quarters to provide sub-samples for experiments. However, it is understood that many tasks, particularly various kinds of petrographic analyses, will require samples extending across the entire core diameter. The steering committee will make a good faith effort to balance immediate requests with the need to retain representative sections of the core on a semi-permanent basis. More than 5 years after the core is obtained, we hope that the Geological Survey of Oman will take on the task of processing and responding to sample requests. We propose that construction and operation of the core storage facility be funded and overseen by the Omani Ministry of Industry and Commerce.

In practical terms, we envision an international drilling effort led by European, American, Omani, and Japanese investigators, and supported by a combination of the International Continental Drilling Program, national science foundations, and industry sources. We were aided in preparing an earlier planning letter by Mr. Roland Lawrence of the Ocean Drilling and Continental Drilling Programs, who prepared a preliminary financial estimate. Mr. Lawrence estimated that a 1 km diamond drill hole in Oman would cost about $400,000, including the non-standard cost of trucking sea water from the coast. In the rare cases where helicopter support would be required to transport a drill, the cost would be closer to $450,000. Dr. Kevin Burke of the ICDP Scientific Advisory Group has expressed the opinion that Mr. Lawrence's estimate is unrealistically expensive. If so, then the value of $400,000 can be considered a conservative upper limit for the cost per hole. In any case, this estimate should be viewed as preliminary. It will be refined during the proposed planning workshop in Oman. We have learned that there is at least one local diamond drilling contractor, Lalbuksh Drilling Company in Muscat. With a cost of $ 60,000, LDC has provided us with a lower bound for opening a road and providing water to the well site, mobilizing and demobilizing the rig, and boxing 500 m of core.

Hence, the startup cost for each hole will be approximately $50,000 to 80,000, and more if helicopters are required. Because this cost is large, and largely independent of the final depth, there is little point in drilling shallow holes to "save money". However, it is equally true that standard wireline diamond drilling often becomes problematic at a hole depth of 500 to 1000 meters, mainly due to a loss of control over the hole geometry. After this, the cost per unit length of drill core rises rapidly. *Thus, our plan is to drill holes from 500 m to 1000 m in length, and to determine the optimal depth during drilling, based on drilling conditions in each specific hole.*

The downhole, geophysical logging program is estimated to cost up to an additional $100,000 per hole. As for the analysis of drill core, it could be funded jointly by ICDP and granting institutions in the home countries of the individual investigators.

In the long run, we propose to drill 8 to 10 holes. However, given the cost for each hole, we realize that such a large project cannot be undertaken by the ICDP in a single step. Instead, we anticipate that the project would be conducted in a series of steps, each designed for maximum scientific benefit in its own right. Successively, these steps would gradually prove the utility of the technique and the ability of the investigators to provide important scientific results. Therefore, **in our first formal proposal to the ICDP, we would request funding for two drill holes**, one through the transition from igneous crust to mantle peridotites, and one through the transition from sheeted dikes to gabbros.

Relation to other scientific initiatives in the Oman region

The proposed drilling program will complement the **GEOman** project by US and European scientists, led by Dr. S. Constable, W. Wilcock (USA) and B. Ildefonse (France). Geophysical experiments at 100 m- to 6 km-scale (seismic, electrical, electromagnetic) were conducted within the ophiolite mantle and igneous crust (Figure 1). Coordination of these efforts may permit drilling of specific seismic boundaries (reflectors or changes in seismic velocity) that could be imaged by larger scale geophysical measurements. At this stage of the project, we wish to site our drill holes in the Sumail and Wadi Tayin massifs, which are the best studied in the ophiolite. These massifs are also close to the Seeb International Airport which serves Muscat, and have drill sites only tens of km from towns.

Societal impact of the project

The societal impact of the proposed drilling program is mostly limited to regional benefits, with relations to water storage capacity and delivery from the ophiolite complex, as well as possible aspects related to the description and analysis of mineralization processes of the lower crust and upper mantle (chromite, platinum group).

Scientific rationale - some examples

Some fundamental issues regarding mid-ocean ridge processes are now very well posed, based on two decades of intensive research, and now await definitive solutions. An Oman drilling program, coupled with continued international emphasis on drilling and sampling active ridges, could provide such solutions within the next ten years. In what follows, we give a few specific examples.

(1) **Lower crustal accretion**: Two different hypotheses for the formation of the crust are clearly delineated. In one, the "conveyor belt" hypothesis, all of the plutonic rocks in the oceanic crust undergo ~90% of their crystallization in a shallow magma chamber, and then ductilely flow downward and outward to form the lower crust. In the other, the "sheeted sill" hypothesis, plutonic rocks are emplaced at a variety of depths within the crust forming at a spreading ridge, with later compaction but little or no vertical transport by ductile flow. Both of these end members clearly play a role in forming the crust, but their relative importance is important and unknown.

One key element in addressing this question will be investigations of geochemical variation in lower crustal gabbros. It is already known that they exhibit extensive, non-systematic variation as a function of height above the crust/mantle transition zone (Figure 2). Because of this, 100's of samples along a representative transect must be analyzed to determine whether there is any general variation, or whether the data are consistent with formation of some of the rocks - regardless of vertical position in the crust - in a single, shallow magma chamber.

Furthermore, the presence of irregular, vertical variation in mineral compositions can be used to constrain magma migration processes. The data of Figure 2 have been used to show that, after initial crystallization of the igneous minerals, large volumes of melt cannot have migrated through the crust by diffuse porous flow over length scales larger than the sample spacing (ca. 50 meters). This in turn implies that there was not an interconnected network of melt in the crust on those length scales, which places limits on the bulk viscosity and tensile strength of the solid+melt aggregate in the lower crust beneath oceanic spreading ridges. The bulk viscosity must be high, and most of the melt that forms dikes and lavas in the upper oceanic crust must migrate in conduits of focused flow - probably in cracks.

Another striking thing about Figure 2 is that almost every sample represents an inflection point in plots of composition vs crustal depth. The actual wavelength of chemical variation with height is unknown. Determination of the scale of systematic compositional variation with height (centimeters to meters in gabbros near the crust/mantle transition; Korenaga & Kelemen, 1997) provides important constraints on the porosity of the plutonic rocks after initial formation of "cumulate" crystals, and on the mode of melt migration through the lower crust to feed the overlying dikes and lava flows.

(2) **Size/frequency distribution of melt extraction conduits, dikes, and veins**: Two different paradigms, porous flow and melt extraction in fractures, have been proposed to explain the extraction of mid-ocean ridge basalt from its mantle source. While both of these processes certainly operate in some times and places, their relative importance is uncertain. Both produce a distinctive rock type, called "dunite". An key feature of dunite conduits is their size/frequency distribution. The number of large conduits determines the extent to which melt can migrate through the mantle without equilibrating with the surrounding solids, and the slope of the size/frequency distribution may be diagnostic of the nature of the melt migration process. we have recently completed detailed mapping of dunite distribution in a single outcrop of mantle peridotite in the western US, and found that the dunite distribution shows a power law (fractal) relationship between size and frequency. Similar studies in Oman would be very difficult. Observations of dunites in Oman are hampered by the presence of extensive, near-surface alteration of mantle lithologies, and by "desert varnish" - a black oxide coating that obscures the outcrop surface. Furthermore, in any locality, because of the irregular, discontinuous nature of outcrop exposures, it is difficult to collect size/frequency data on the distribution of dunites over areas larger than a single outcrop. Drilling will facilitate collection of a less altered, representative sample suite. Similar studies could be conducted on drill core throughout the Oman crustal section, to determine distribution of basaltic and gabbroic dikes, ductile shear zones, alteration veins, and brittle cracks.

(3) **Lower crustal deformation**: In considering the igneous and kinematic processes of oceanic crustal accretion, it is vital to quantify the strength of rock fabrics along a representative transect. In the "conveyor belt" hypothesis, rocks formed in a shallow magma chamber and transported downward and outward should show increasingly intense deformation fabrics with increasing depth in the crust. However, the possible presence of plutonic sills intruded into the conveyor belt complicates this test, and requires systematic study of a representative transect rather than surface sampling. One consequence of large strains would be thinning of pre-existing igneous layering. Thus, the conveyor belt hypothesis predicts that on average igneous layers should be thinnest near the base of the crust. Observations of drill core can be linked to downhole geophysical logs to provide a continuous, high resolution determination of layer thickness as a function of depth.

(4) **Mantle flow**: For a broad segment of our community, the most important issue for understanding ocean ridge processes is the geometry of mantle flow below the Moho. Investigators working in Oman have identified a series of diapiric structures in the peridotite which have been interpreted as frozen, ridge axis diapirs, and therefore as indicative of a three dimensional upwelling geometry for the partially melting mantle beneath oceanic spreading ridges. Although this hypothesis has achieved wide acceptance in some circles, other investigators question the importance of this process at fast-spreading ridges, and still others note that the scale of the Oman mantle diapirs is much smaller than the spacing of gravity lows, interpreted as diapirs, along the Mid-Atlantic Ridge. Further complications have arisen with recent hypotheses that some of the diapirs disrupt older mantle and crustal structures, and represent off-axis seamounts or the leading ends of propagating ridges.

A crucial element in reconstructing the kinematics of diapirism is to investigate the structure in the area of corner flow; whereas steep and shallow mantle structures have been observed, the transition from one to the other has remained elusive. Drilling, with the potential to gather representative sections of unaltered rock, and the potential for statistical characterization of systematic variations in fabric strength and orientation, can greatly help in addressing this problem. Cross sections based on field observation and interpretation identify many areas in the Sumail massif of the Oman ophiolite where peridotite with vertical lineation at depth is overlain by peridotite with horizontal lineation immediately beneath the crust mantle boundary (Figure 3). Between the two, if the diapir interpretation is correct, there must be a zone of inclined lineations where flowlines "turn the corner".

Furthermore, because the transition from steep to horizontal lineations is very shallow, it has been proposed that a huge volume of upwelling peridotite passes rapidly through a very narrow vertical interval beneath the crust. This is thought to form a kind of shear zone within the crust/mantle transition zone, because in that narrow region the mantle peridotite must have horizontal velocities many times greater than the crustal spreading rate. Within this shear zone, there must be an inversion in the shear sense (Figure 4). Although some preliminary field data support this hypothesis, drilling will test the generality of this result and quantify the magnitude and history of strain.

(5) **Igneous composition, and hydrothermal metasomatism**: Although it remains uncertain to what extent the Oman ophiolite represents a truly typical sample of crust formed at a mid-ocean ridge, it did form at a submarine spreading ridge and is the most best exposed example of such crust on land. Systematic geochemical study of a representative section will provide valuable insight into such outstanding problems as the bulk composition of the oceanic lower crust, and the depth and extent of chemical changes due to high temperature hydrothermal alteration. These data, in combination with analyses of samples from active ridges, will be of fundamental importance in determining geochemical fluxes at spreading ridges and where oceanic crust is returned to the mantle in subduction zones. In turn, these fluxes are a vital link in ongoing programs that seek to characterize Earth system science.

In the mantle section, systematic alteration studies will be unprecedented and valuable. If much of the alteration in outcrops is due to surficial processes, as we suspect, then drilling has the potential to obtain samples that are more representative of the oceanic mantle lithosphere in terms of the extent and type of alteration. These data, in turn, can be used to estimate subducted fluxes of some elements - such as B - that are concentrated in altered peridotites. In addition, systematic determination of the presence or absence of a vertical trend in primary, residual peridotite compositions will be valuable in constraining melting and melt migration processes in the shallow mantle beneath spreading ridges.

(6) **Correlation of crustal lithostratigraphy and seismic structure:** For the past 30 years, the seismic, density, and magnetic structure of oceanic crust inferred from marine experiments has been correlated with a crustal lithostratigraphy which has largely been derived from ophiolite investigations. In particular, seismic layer 2 has been associated with extrusive basalts and sheeted dikes, while seismic layer 3 has been identified with the gabbroic section in ophiolites. Similarly, the seismic Moho has been interpreted as the boundary marking the transition from lower crustal to upper mantle rocks. However, there is increasing evidence that in some localities the seismic properties of the oceanic crust are primarily controlled by its bulk porosity and state of chemical alteration rather by

igneous rock type. Thus, it has been suggested that the seismic layer 2/3 boundary does not mark the boundary between sheeted dikes and gabbro, but may be a porosity boundary within the sheeted dike section, while the Moho, at least in some settings, may correspond to an alteration boundary between serpentinized and unaltered ultramafics, rather than the base of the igneous crust.

Attempts to address these problems in the modern oceans by correlating core samples and logging results from drillholes with large-scale seismic structure have been frustrated by poor core recovery and depth limitations. While fracturing and alteration of the Oman ophiolite may differ from that of in situ oceanic crust, it should nevertheless be possible to examine the importance of factors such as igneous rock type, bulk porosity, and alteration on the seismic response using in situ physical properties, determined by logging and measurements on core samples, and larger scale borehole seismic and conventional refraction/reflection profiling. For example, is the downhole variation in crustal bulk porosity or lithostratigraphy more important in controlling the seismic response at the dike/gabbro boundary? Does the layering of gabbros in the lower crust in Oman yield a distinctive signature at seismic wavelengths of 100s of meters that might be identifiable in marine refraction data? What is the seismic signature of the Moho transition zone and how is it affected by alteration, such as may be common at slow spreading ridges where the crust is quite thin. A pilot seismic experiment, to examine some of these questions, will be conducted in Oman in early 1998. Thus, studies of core, downhole logging, and borehole and conventional seismic studies, together will provide quantitative constraints on the relationship between seismic structure and igneous stratigraphy of oceanic crust.

Tentative identification of drill sites

The following is a prioritized list of potential drill sites, in order of priority. This list is preliminary, and is offered as an example of what drill sites are practically available in the Sumail and Wadi Tayin massifs of the Oman ophiolite. For locations, see Figures 1, 5 and 6.

1. Drill hole through lower crustal gabbros and the crust/mantle transition zone, Wadi Gideah section of the Wadi Tayin massif. This hole would eventually be the deepest in a full transect of the Wadi Gideah crustal section. The section in this area was studied by John Pallister, USGS geologists led by Robert Coleman, and Pallister's advisor Cliff Hopson, and later by the Tectonophysics group at the Université de Montpellier. It was shown to be 5 to 7 km thick, similar to "normal" oceanic crust, and to have gabbro and dike chemistry consistent with crystallization from magmas very similar to mid-ocean ridge basalt. This drill site would require helicopter transport of a drill for one to three km beyond the end of the passable road. (Note that helicopter transport of diamond drill rigs is a standard technique among mineral exploration geologists). However, all other proposed drill sites in Wadi Gideah would be accessible by road.

2. Drill hole from sheeted dikes into upper gabbros, Wadi Gideah section of the Wadi Tayin massif.

3. Drill hole through lower gabbros and the crust/mantle transition zone, Wadi Kurah section of the Sumail massif. This hole would penetrate the lower half of a crustal section which is much thinner than in the nearby Wadi Tayin massif (Nicolas et al., 1996), to examine the extent of lateral variability along a key horizon at the base of oceanic crust.

4, 5. Two mantle peridotite drill holes in (a) vertically lineated peridotite in the center of the "Maqsad diapir" structure in the Sumail massif, and (b) horizontally transposed peridotite along the periphery of the Maqsad structure.

6,7,8,9,10. Drill holes linking the sections sampled by holes 1 and 2, to obtain a full lower crustal sample from the Wadi Gideah section of the Wadi Tayin massif.

Three important questions, and our response

We anticipate three important, critical questions about this proposal, and address them here.

- The Oman ophiolite is well exposed, in a desert region with deeply dissected canyons, so why is drilling necessary? In fact, the ophiolite is deeply weathered; oxide coatings obscure contact relationships, particularly in the mantle and Moho transition zone, and alteration associated with shallow circulation of ground water impedes geophysical, petrographic and geochemical measurements. Also, because the canyons are deeply incised, meandering, and joined by innumerable branches, it is impossible to collect representative vertical sample sections. Extensive mapping already completed, and mountainous exposures, do provide an unparalleled opportunity for choosing drill sites, and for correlating "stratigraphy" from one hole to another.

- Ophiolites are not necessarily representative of normal mid-ocean ridges, so why study them? It is plain that ophiolite research has provided fundamentally important insights to those studying active, submarine spreading systems, in a productive, ongoing dialogue. While the Oman ophiolite may not be typical of a "normal" mid-ocean ridge in every respect, the presence of pillow basalts underlain by a continuous layer of sheeted dikes establishes beyond doubt that it formed at a submarine spreading center. The processes that formed the igneous crust in Oman were similar to those at mid-ocean ridges. Geochronological and geological data, including the presence of a continuous gabbroic layer between dikes and mantle peridotite and the general absence of large fracture zones (e.g. Tilton et al. 1981; Nicolas & Boudier 1995), suggest that the ophiolite formed at a fast spreading ridge. Thus study of the ophiolite can provide important insight into processes at fast spreading ridges. Drilling in Oman will be complementary to the continuing efforts of the Ocean Drilling Program. Results from Oman cannot be correctly interpreted without complementary results from modern mid-ocean ridge systems.
- Given the existing results and core from the Cyprus Crustal Study Project, why conduct a drilling program in another ophiolite? Drilling in Oman will be complementary to previous drilling in Cyprus. First, we can anticipate from the Cyprus results that the core recovery will be excellent, much better than for drill holes from the Joides Resolution at sea. This presents a great opportunity, since downhole logging of ophiolite holes combined with good core recovery can be used to calibrate the logging techniques for use by ODP in holes with poor recovery. Unfortunately, in Cyprus there was no geophysical logging of the holes; this is one of the chief motivations of our drilling proposal for the Oman ophiolite. Second, the Cyprus drilling did not obtain a full crustal section, and in particular lacked core from the crust/mantle transition zone and the upper mantle. Third, it will be much easier to place Oman drill holes in geological context, because of the exceptional outcrop exposures . Finally, because the Oman ophiolite is one of the largest in the world, it will be easier to choose Oman drill sites that are representative of typical crustal sections over more than 250 km along strike.

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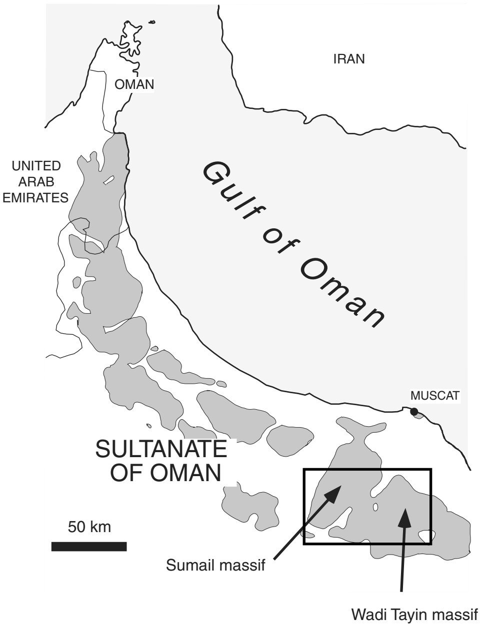


Figure 1 (above): Outcrop area of the Oman ophiolite (grey), redrawn after Lippard et al., 1986. Rectangle indicates approximate location of geologic map in Figure 5.

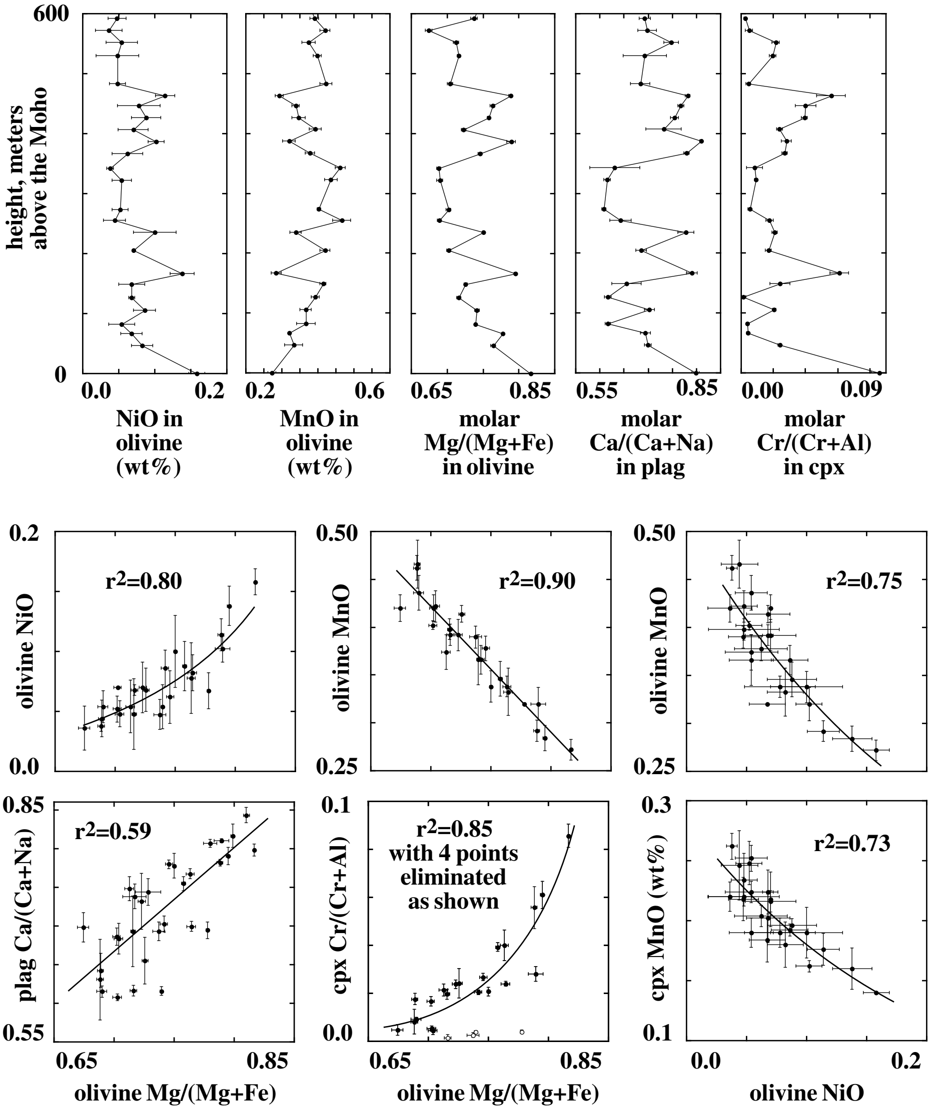


Figure 2 (right): Variation of mineral chemistry in lower crustal gabbro from the Oman ophiolite, compiled by Korenaga & Kelemen (1998) from the PhD thesis of Paul Browning (1982) at the Open University. Mineral compositions show no regular variation with height above the Moho, but are strongly correlated with each other. Korenaga & Kelemen (1998) argued that this precludes substantial migration of melt by diffuse porous flow through the lower crust after crystallization of the igneous minerals. Note that almost every sample constitutes an inflection point in plots of height vs. mineral composition, so that the actual length scale of chemical variation is unknown. Analyses of drill core will provide detailed measurements on a nearly continuous section.

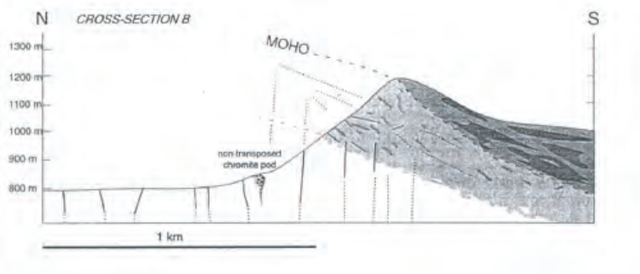
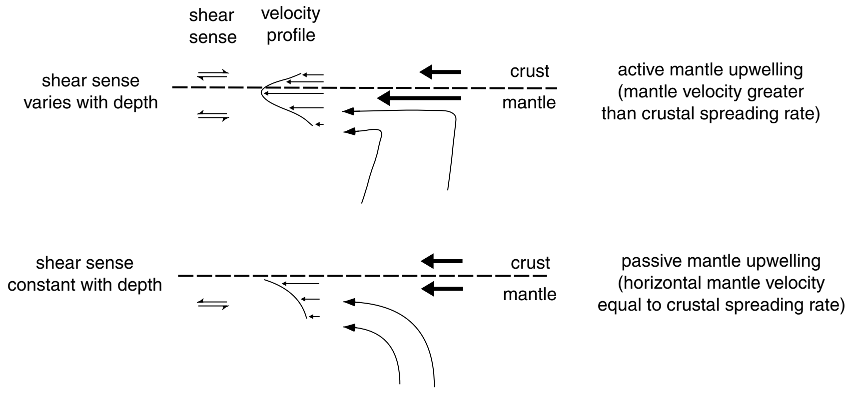


Figure 3 (left): Cross section in residual mantle harzburgites, plus dunites (grey) and gabbro (dark) along the crust/mantle transition near Wadi Kurah (figures 5 and 6) in the Sumail massif of the Oman ophiolite, from the PhD work of David Jousselin with the Tectonophysics group at the Université de Montpellier (paper submitted to Journal of Geophysical Research, 1997). Straight lines indicate dip of lineation, and show how near veritical lineation extends to within one or two hundred meters of the Moho, and is directly overlain by peridotite with nearly horizontal lineation. If the structure in this area was formed by diapiric mantle flow, upward at depth and then outward just beneath the Moho, then drilling should sample the transition between vertical and sub-horizontal mantle flow regimes. Alternatively, if the vertically lineated mantle was "intruded" into pre-existing oceanic lithosphere, for example due to ridge propagation, then an "angular unconformity" should be observed.

Figure 4 (right): Schematic illustration of the predicted inversion in the shear sense near the crust/mantle transition zone, for oceacic crust and uppermost mantle formed as a result of active mantle upwelling, contrasted with consistent shear sense predicted for passive mantle upweling, drawn after Nicolas et al., 1994. Drilling should provide statistically robust indications of the presence and strength of variation in shear sense with depth.



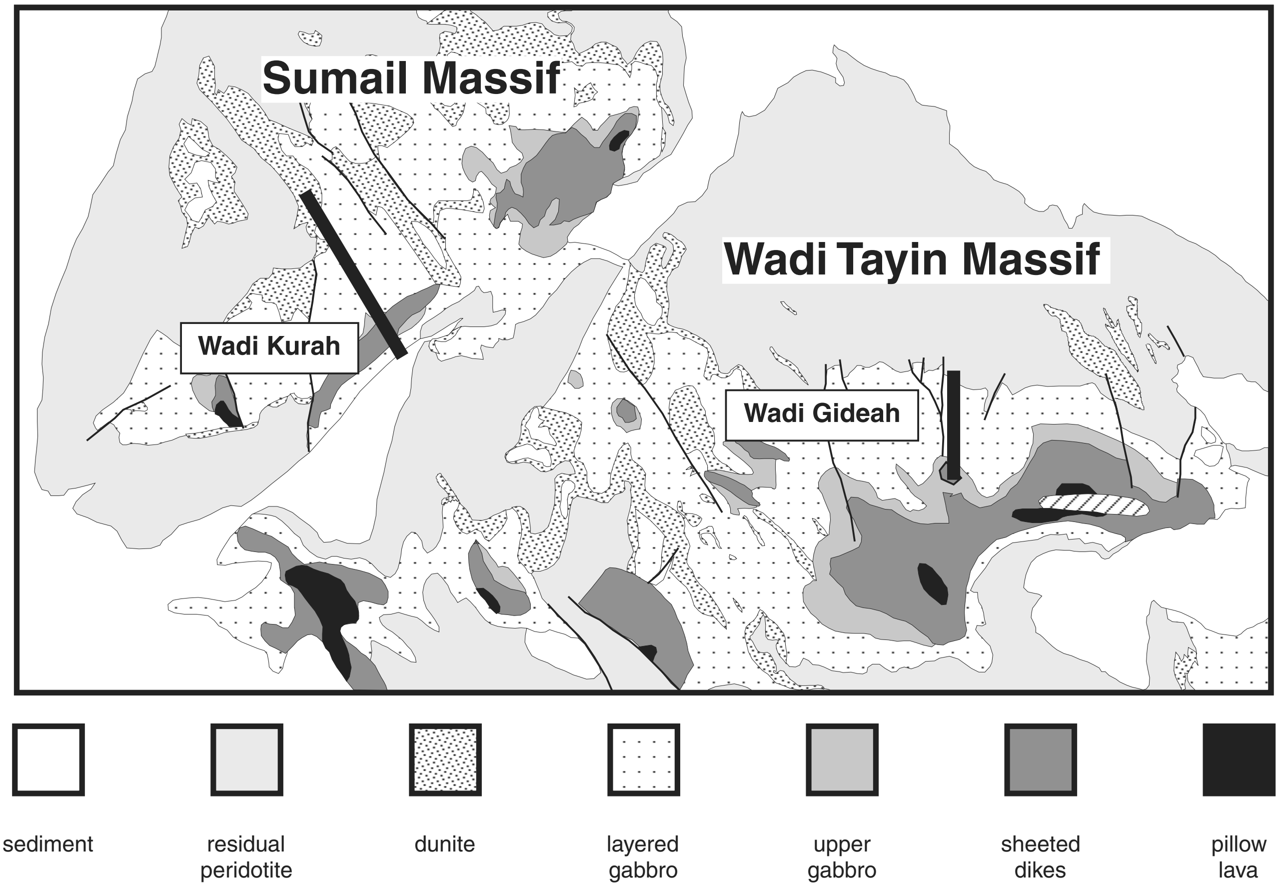


Figure 5: Geologic map of Wadi Tayin and Sumail massifs, showing location of cross-sections in Figure 6. Redrawn from unpublished map compiled by the Tectonophysics Group, University of Montpellier, ca. 1995.

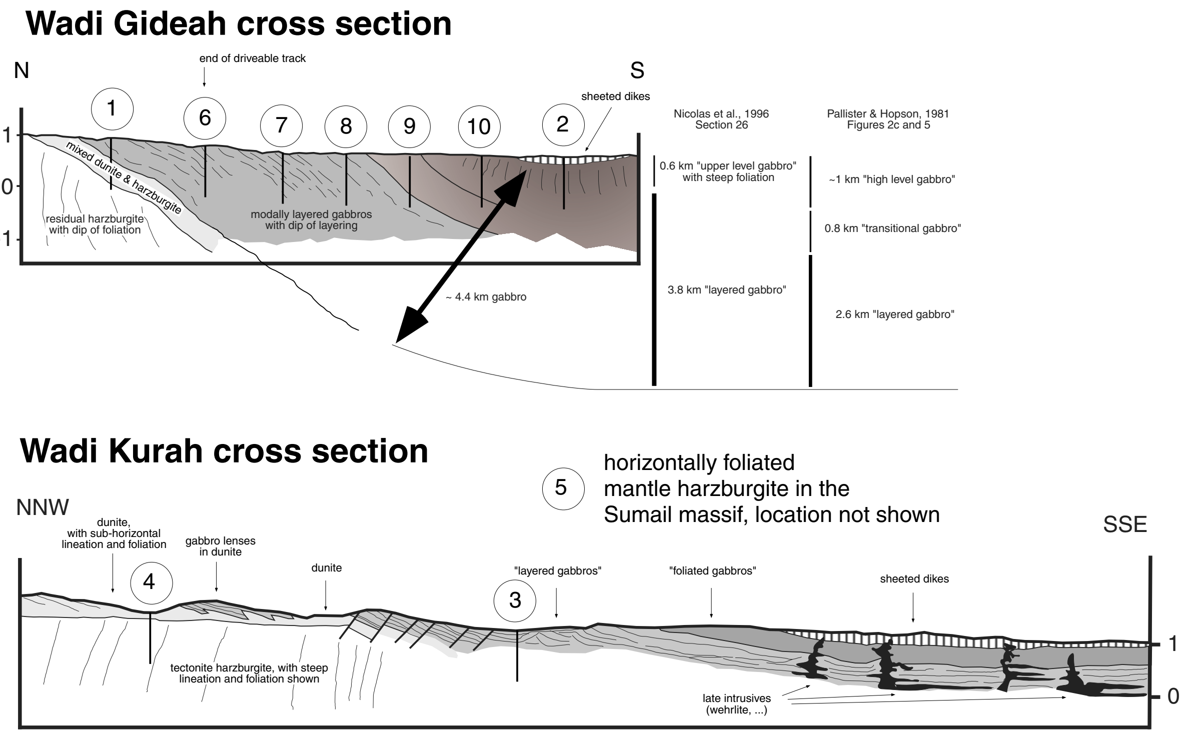


Figure 6: Cross sections of parts of the Wadi Tayin and Wadi Sumail massifs, as indicated in Figure 5, with proposed drill sites marked with vertical lines 1 km long, and numbered in order of priority. Data for Wadi Gideah cross section from Pallister & Hopson (1981) and Nicolas et al. (1996). Data for Wadi Kurah cross-section from Françoise Boudier (personal communication, 1998). Both sections are at the same scale, with no vertical exageration, and elevations in kilometers.

White paper for Mission Moho 2006

April 24, 2006
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This may be re-iteration of what I said in the “Statement of Interest” as well as what appeared in the workshop web, but I’d like to note that the following points should be seriously considered:

(1) Consideration of contrasting or complementary environments – variations in spreading rate, mantle temperature or tectonic setting (Godzilla Mullion)
(2) Consideration of drilling into deep crustal “windows” in core complexes and other faulted exposures such as Hess Deep (also Godzilla Mullion)
(3) Appraisal of existing deep holes (Hole U1309D at Atlantis Massif, and Hole 735B at Atlantis Bank)

Logistically, we may want to develop a mission proposal of IODP (i.e., CDP proposal). This mission proposal will include a proposal of deep drilling with the Chikyu at super-fast environment, Godzilla Mullion proposal, Hess Deep proposal, 735B deep proposal, and potential U1309D deepening proposal.

Apart from the above, I have a concern about how do we produce a continuous, quantitative geochemistry data from core using an X-ray core-logger. On the Chikyu, there will be the machine, and the data shall be obtained routinely; so there will be no problem. Although, I’m not sure about the status on the new SODV, we have to make consideration of the already-taken-cores from the Joides Resolution (e.g., especially cores from Hole U1309D). One idea is that these U1309D cores should be sent to Kochi, where an X-ray core-logger is installed. The continuous, quantitative geochemistry data for the entire cored length will be very important data for comparing/understanding oceanic lithosphere magmatic processes from different spreading environments.

End

Drilling to the Moho with IODP: lessons from the past and the need for Interactive Drilling Operations

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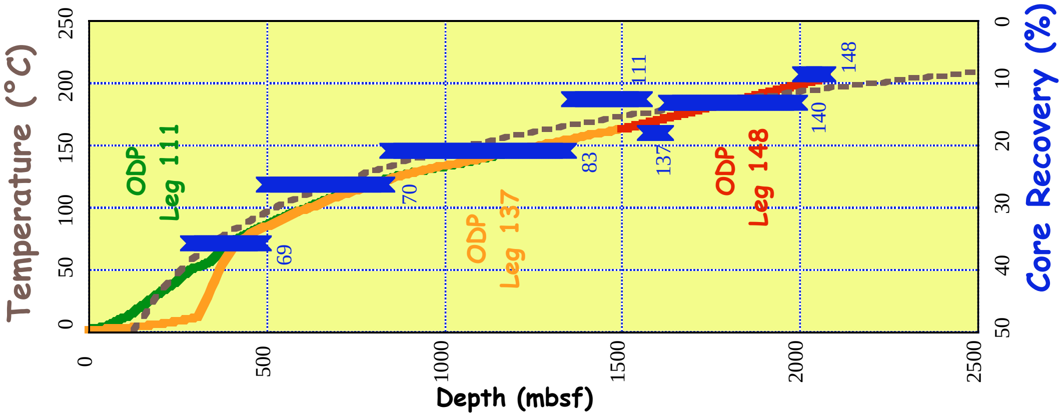
Drilling deep into the basaltic oceanic seafloor and crust has been a goal of the scientific community for now more than 40 years. However, while penetrations of the Earth crust of more than 12 km have been achieved on land, the deepest hole drilled yet into the ocean floor (DSDP/ODP Hole 504B) extends merely beyond 2 km. In spite of the substantial time devoted to the drilling of this record hole, the lack of planning for deep penetration, as well as the absence of real-time control and monitoring during and between drilling phases, are the main causes of the present results.

The challenges associated with drilling deep (about 5 to 7 km) into hot (about 250°C) oceanic crust in the context of IODP can be extrapolated from what was learned overtime with the JOIDES Resolution. This abstract summarizes the main geological and technical difficulties met by ocean drilling in the past, and proposes approaches to overcome some of them. First of all, circulating drilling fluid through more than 3 km of cold ocean water is an extreme source of thermal stresses and borehole instability. In the case of ocean drilling with a riser-less system, the drilling fluid enters the crust at sea-floor level and a temperature of about 2°C, generating very high thermal stresses during drilling. With a riser (as for Chikyu), a closed circulation system allows one to drill with hot fluid, which helps to minimize thermal stresses and associated borehole instabilities. However, it is more the actual changes in temperature over time, and associated transient stresses, that might be the cause of borehole surface ruptures, than the actual. Let us review now the main achievements of deep drilling into hot oceanic crust.

Figure 1

Decreasing core recovery with increasing depth into the crust in DSDP/ODP Hole 504B, Costa Rica Rift. The core recovery decrease tends to follow the increase with depth in temperature measured at so-called "equilibrium", when the hole is first re-entered and before coring begins.

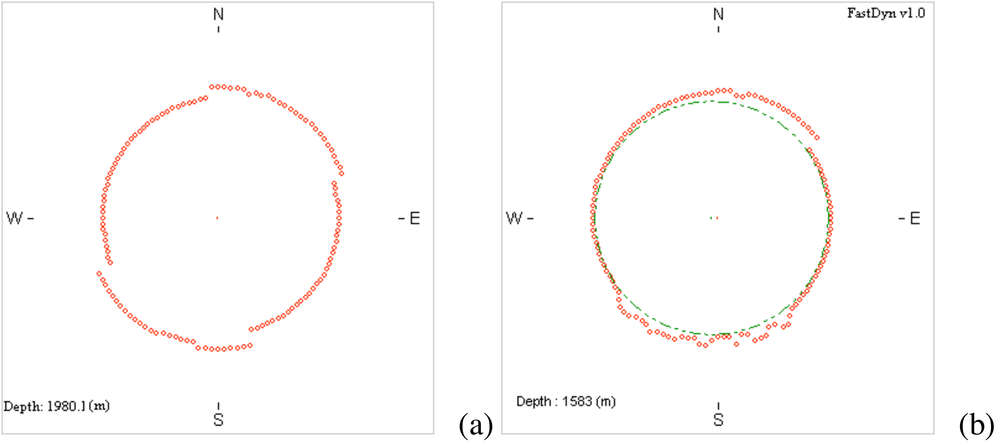


DSDP/ODP 504B is located in the Pacific on the Nazca Plate, south of the Costa Rica spreading center. The drilling started with DSDP Leg 69 (1979) and reached a depth of 2111 m below sea floor (mbsf) during ODP Leg 148 (1993), where a fault zone in which the drill-pipe became stuck was encountered. Temperatures up to 190°C were measured at about 2000 mbsf. At this depth, the core recovery was lower than 10 % (Figure 1) and thermo-mechanical modeling of the drilling process showed the direct link between temperature and poor core recovery. The hole was, in fact, not initially designed to reach deep, preventing the deployment of a casing program below the sediment cover, and giving way to borehole caves to develop. Drilling became as a consequence increasingly more difficult with depth, at a rate exceeding largely that traditionally encountered.

The ups and downs of drilling the bottom thousand meters of Hole 504B left the scientific community with a series of technical and scientific questions concerning borehole stability. Two main types of problems due to instabilities from thermal and tectonic origin were observed to develop: (1) the drill pipe getting stuck, either abruptly or gradually during drilling, and (2) the loss of drilling material in the hole. While the latter was partly solved with a conservative drilling strategy during the last two drilling legs, the former has been given no satisfying answer up to now. However, borehole wall instabilities were mapped from cm-scale acoustic images of the borehole surface (Figure 2), revealing (1) the presence of tensile ruptures from thermal (Figure 2a), and (2) the rupture of active fault planes crossed by the hole (Figures 2b and 3).

Figure 2

(a) NE-SW borehole elongations due to near vertical tensile fracturing in the direction maximum horizontal stress (determined from breakout analyses at shallower depth in the hole) from thermal stresses. (b) Borehole elongation in the NE direction due to right-lateral shear along a near vertical (based on fracture mapping from borehole wall images) NE-SW striking plane, then wear of the low side of the hole (inclined 5° to the NE) located here W-SW.



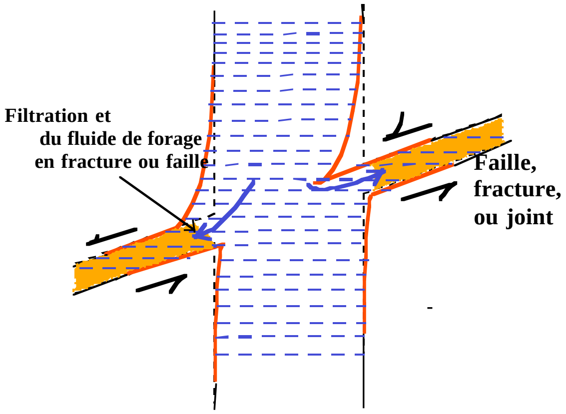
Tensile ruptures due to cooling from mud circulation were first found to be associated to fishing, packer experiments, or logging operations (Morin et al., 1990), as well as re-entries into the hole. Numerical modeling indicates that, during drilling, thermal stresses are strongly dependent upon mud-flow rate, and reach a maximum after one to two hours of circulation. The presence of a riser, if somewhat thermally insulated from cold ocean waters, minimizes such thermal stresses during drilling. With real-time measurements of torque, flow-rate, input and output temperatures, the thermal regime of the hole might be monitored and modeled in real-time and continuously, this in order to minimize and thus control borehole instabilities.

This evaluation is essential as each degree of cooling at 2000 mbsf in Hole 504B (where the vertical load is about 92 MPa) generates a thermal stress of about 0.83 MPa. As a cooling of 120°C might be reached at the drill-bit with a JOIDES-like riser-less system, an effective vertical stress reduction of 100% can be expected, resulting in core disking along saddle-shaped sub-horizontal planes. These large extensional stresses applied to the core and borehole surface also favor shear ruptures on pre-existing planes.

Tectonic instabilities are, respectively, less known prior to drilling and, consequently, more difficult to anticipate. Staying away from large faults revealed by seismic profiles is certainly the most efficient way to minimize such difficulties. Once a site selected, the repeated recording and differential analysis of acoustic images, at the beginning and at the end of each drilling phase, can provide a detailed description of tectonic mechanisms by which the drill-pipe might get caught (Figure 3). Time-lapse measurements might also lead to evaluating strain rates along fault planes due to drilling. In all, downhole images can be used to identify tectonically active intervals. In turn, a real-time and continuous control of drilling parameters should contribute to reduce shearing along active fault planes.

Figure 3

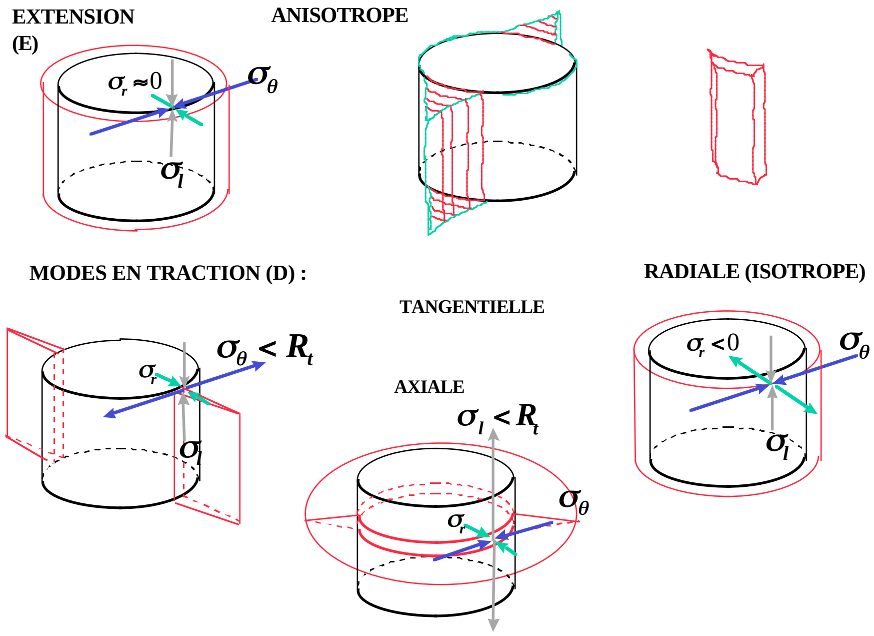
Borehole shear due to stress release associated with drilling along a pre-existing fault plane. Such a shearing movement might result in a stuck pipe, as sometimes encountered in Hole 504B, especially at the base (2111 mbsf) when the hole was lost after entering abruptly a zone where the coring rate increased from an average 0.5 to 1.0 m/hour in the overlying dikes, to about 7.0 m/hour within. Similar situations where also met more recently below 1000 mbsf in Hole 1256D.



In Hole 504B (Pezard et al., 1997), the normal faults created in a rhythmic manner at the Costa Rica ridge axis and with near vertical walls at the sea floor were found to dip toward the axis at a somewhat shallow angle (between 40 and 55 degrees) and a relatively shallow depth into basement. The mapping of fracture planes from FMS electrical images of the borehole wall provides a direct proof of these shallow dipping features within the main fault zone (800 to 1100 mbsf; Figure 3). Similar results were obtained in the Atlantic from the analysis of extensional earthquake focal mechanisms near the ridge axis (Thatcher and Hill, 1995). These faults are found in Troodos to shallow even further, merging at depth within strain accomodation zones at major lithological boundaries (Agar and Klitgord, 1995). Similar near-horizontal mechanical discontinuities are to be expected in deep holes aiming for the Moho. Shallowing down towards the ridge axis, these faults may alternatively merge with the inward dipping stratigraphic structures of the lavas in the upper crust (Palmasson, 1973; Rosencrantz et al., 1983; Christeson et al., 1992; Pezard et al., 1992). While relatively contrasted in a mechanical sense with respect to the surrounding crust, these faults now visible in the seismic record are, however, not the only ones that might result in shearing of the borehole during coring operations.

Figure 4

Various modes of borehole failures in tension, which might appear as a result of thermal stresses (after Maury). These include near-vertical, near-horizontal and radial fracturing in tension. A combination of these tensional modes might result in borehole cross-sections such as that obtained in Hole 504B at 1980 mbsf (Figure 2a).



In conclusion, adequate planning, as well as continuous, real-time monitoring and modeling of the thermo-mechanical status of the borehole during (and in between) coring operations appears as a key to succeed in drilling deep into hot oceanic crust and to the Moho. Modeling and monitoring will contribute to minimize borehole instabilities and prevent a number of drilling accidents in this context. In addition to standard well planning for deep drilling, IODP should design from the start strategies to monitor hole stability prior to drilling (numerical modeling), during drilling (Measurements While Drilling or "MWD" if possible, and the recording of drilling parameters at surface) and after drilling (differential inspection of repeated acoustic borehole wall images), hence following the ongoing evolution of the drilling industry towards the development of more interactive, rather than passive, drilling methods.

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White paper for consideration
John Sinton

There are a large number of important magmatic process at mid-ocean ridges that can be addressed with drilling through a complete section of oceanic crust and upper mantle. These can be grouped into various categories according to the depth level in the system: (1) from magma chambers to the surface (how magma chambers are tapped during diking and eruptive events, why and how dikes and lavas commonly leave behind much of the crystalline portion of magma chambers, the extent to which dikes travel vertically or along-axis); (2) from the Moho to magma chambers (the extent and nature of interaction with lower crustal materials, the development of single versus multiple magma chambers, the extent of sill-like intrusions at various levels in the lower crust, the development of fabric in oceanic gabbros); (3) Moho and upper mantle (the evidence for magma pooling at the Moho, the nature and extent of interaction of migrating magma with upper mantle materials, etc.). Processes in each of these environments has implications for how we think about the bulk constitution of the oceanic crust as well as the complete history of magma parcels from melting to eruption.

Although much can be learned from various tectonic windows and outcrops of opportunity, there are many advantages to sampling complete, relatively undisturbed sections that preserve the entire section from erupted lavas to upper mantle. Among the advantages is the obvious one – the potential for investigating and then integrating the results from different parts of a single system that likely represents a limited range of time. How much chemical variation will be found from top to bottom of the system and what are the processes occurring at each level that contribute to this variability?