FINAL DRAFT

THE OCEAN LITHOSPHERE & SCIENTIFIC DRILLING INTO THE 21ST CENTURY

WOODS HOLE, 26-28 MAY 1996

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EXECUTIVE SUMMARY

Introduction

The oceanic lithosphere is formed as a consequence of two major kinds of apparently unrelated processes: the result of ongoing shallow mantle up-welling driven by the motions of the earth's plates at varying rates beneath the oceans, and by the more intermittent process involved in the emplacement of large igneous provinces (LIPs) driven by deep mantle circulation. Over a hundred scientists met at Woods Hole on May 26-28, 1996 to discuss the formation of the ocean lithosphere and how it could be explored through scientific drilling into the 21^{st} century. This meeting was held in the context of the InterRidge and LIPs initiatives which directly address the two components controlling the formation of the lithosphere and whose prior planning forms the basis for this integrated workshop. This report presents an integrated drilling strategy in the framework of the present Ocean Drilling Program (1998-2003) and a future program involving deep-drilling capabilities for beyond 2003 without which this community believes it would be difficult to ever fully understand the evolution of the ocean crust and mantle over some two thirds of the earth.

General recommendations

The workshop participants recognize that scientific drilling in the oceans is required in order to meaningfully advance our knowledge of the oceanic lithosphere. It is the only way to directly constrain models based on indirect measurements, to provide the continuous sampling and stratigraphy required to know the structure and composition of the ocean crust, and to provide boreholes for *in situ* measurements and monitoring of active processes in this living earth.

A two phase strategy is recommended for a systematic focused program of ocean drilling to explore the ocean lithosphere consistent with the ODP Long Range Plan:

Until 2003 (end of Phase II and Phase III of the current ODP): Drilling the ocean lithosphere should be pursued using the drilling capabilities of the *JOIDES Resolution.*

Beyond 2003 (Phase IV): the workshop strongly endorses a two-ship program, including the capacity for deep-drilling (through the MOHO), and the capacity to drill shallower holes on a routine basis with a second technologically less complex and less expensive ship.

MAJOR SCIENTIFIC OBJECTIVES

- To document the active magmatic, tectonic and hydrothermal processes and their temporal variability which control crustal formation at and near ocean ridges.
- Identify the mechanism of formation, timing of emplacement, genesis and environmental impact of the LIPs.
- Determine if sections of fossil ocean crust (ophiolites) exposed on-land in continental margins and island arcs may have formed in the fore-arc environment, and therefore determine the extent to which these sections can be used as analogues for the formation of the modern ocean crust.
- Obtain the needed reference sections of the ocean crust and mantle required to interpolate the composition and structure of the ocean crust across the global ocean basins from geophysical data.

- Determine the processes and locus of formation of representative large ore bodies in the arc-environment — the active analogs to most deposits of economic importance on-land.
- Document the extent of the deep crustal biosphere. Recent work has shown that the biosphere extends much deeper that previously envisioned, well into the crust of the earth, making it the principle unknown component of the Earth's biomass.

PROPOSED STRATEGY

A) 1998-2003 (end of ODP Phase II, ODP Phase III)

During this phase, the drilling capabilities of the *JOIDES Resolution* should be fully utilized to:

- Drill an array of holes at center and distal ends of a representative spreading center to directly constrain variation in crustal architecture and composition at the slow-spreading Mid-Atlantic Ridge.
- Select a site and start the hole as soon as possible in fast-spread Pacific crust and drill into gabbroic crust below the seismic layer 2-3 boundary, as the first stage in proceeding to deep-drilling to the Moho in ODP Phase IV.
- Use the strategy of offset drilling in tectonic windows to: (1) create a composite section of the lower crust and shallow mantle at a fast spreading ridge (Hess Deep); and (2) explore the lateral variability of the shallow mantle in a peridotite belt flanking a slow-spreading ridge segment.
- Define the timing, petrology and geochemistry of four representative LIPs: the two Cretaceous giant LIPs (Kerguelen and Ontong Java), and two representative examples of older and younger LIP emplacement.
- Set up an observatory in conjunction with InterRidge for *in situ* monitoring of active processes by drilling an array of CORKED holes at an axial site, and if zero age drilling is not available, on a ridge flank.
- Drill an andesite-dacite hosted metalliferous deposit in an arc environment to provide an analog for large ore bodies.
- Drill the best possible modern fore-arc potential analog for ophiolites.
- *Evaluate the biomass in every new hole in the ocean crust to document the extent of the deep earth biosphere*

B) Post 2003 (Phase IV)

- There is a consensus that post 2003, the primary target should be to achieve total crustal penetration and drill through MOHO in lithosphere generated at a fast-spreading ridge.
- In addition, the experiment initiated during Phase III to understand the three-dimensional character of slow spread ocean lithosphere should be continued with two holes deepened, preferably to Moho, at the center and the end of a Mid-Atlantic Ridge spreading segment.
- One deep hole and possibly two intermediate holes should be drilled in a LIP, to document the chrono- and lithostratigraphy and to address magma sources and genesis.
- Install seafloor observatories in different environments such as intraplate volcanoes or convergent margin environment.
- Continue the Phase III programs that have not been completed.

TECHNOLOGICAL REQUIREMENTS

The workshop participants stressed that with the capability of the *JOIDES Resolution*, drilling holes to 3-km during Phase III should be feasible with present technology. Necessary technological improvements leading to improved penetration and recovery, particularly in young, fractured basalts — such as hammer-in casing and diamond-coring system — are needed in Phase III. Borehole instrumentation and logging tools should be developed to fit in diamond-cored slim holes.

Many of the Phase IV objectives imply deep crustal penetration (>3-km) and require a ship with deep-drilling capabilities and well control. However, most of the workshop objectives are beyond the reach of a 2500-m water depth conventional riser, and *riserless drilling* or a *slim line riser* should be explored for drilling in waters up to 4000 m. In parallel, a ship with drilling capabilities similar to the present *JOIDES Resolution* should be used to pursue scientific objectives that do not require deep-drilling.

A biology laboratory on the *JOIDES Resolution* should be developed as a matter of urgency along with tools to sample the biota *in situ* without contamination.

RECOMMENDATIONS FOR ODP PROGRAM PLANNING GROUPS

The workshop participants recommend formation of the following program planning groups (PPGs) in concert with the noted global research initiatives:

• RIDGES PPG	*InterRidge, ION*
• LIPs PPG	*LIPs , ION*
• Borehole Instrumentation working group	*InterRidge, ION, Margins*
• Biology PPG	*InterRidge, Margins*

The Workshop considered a convergent margins PPG, but felt that a formal recommendation for this group should come from a broader community involved in arc-related research.

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1 - FOREWARD

The ocean lithosphere & scientific drilling into the 21st century

In the last five decades the oceans have been a major focus of exploration and discovery. With the advent of plate tectonic theory, large scale seafloor mapping, and systematic geophysical survey, there has been the rapid development of new paradigms for the evolution of the oceanic lithosphere which have transformed geologic thinking and our concept of earth history. In recent years, earth scientists have focused on testing these paradigms in the diverse tectonic environments found in the oceans, including fast- and slow-spreading ocean ridges, convergent margins and large oceanic igneous provinces. This has led to a growing appreciation of the limits of surface exploration and an increased interest in drilling, particularly deep-drilling, as the only way to directly test and provide ground truth for the composition and evolution of oceanic crust and shallow mantle.

The last ten years have seen accelerated progress towards understanding the formation of ocean lithosphere at ocean ridges, its evolution with time and fate at subduction zones. National and international programs have been set up by the scientific community to better coordinate the sea efforts: InterRidge and the different national programs (Ridge, Bridge, Dorsales, DRidge, Japan Ridge) have focused their efforts on understanding mid-ocean ridges. LIPs is aimed at understanding the generation of large igneous provinces and the evaluation of their impact on the biosphere and climate. The ION (International Ocean Network) program objective is to complement the existing seismologic network on-land by seafloor/borehole observatories to increase the resolution of mantle seismic tomography. The margin community is also getting organized at the national as well as the international level. The focus of these programs has been geophysical mapping, observation of the seafloor, surficial sampling and remote sensing. However, as knowledge has increased, it has become clear that many of the key observations required to document the structure and the composition of the ocean crust and shallow mantle, and identify the processes of lithospheric accretion can only be made by direct sampling. Given that the required observations are inherently stratigraphic, the only way this can be done is by ocean drilling.

Recent drilling in tectonically exposed lower crust and mantle sections in the Pacific, Atlantic and Indian oceans, for example, appears to confirm that crust formed at fast- and slow-spreading ridges varies dramatically in stratigraphy, structure and state of alteration. This apparently reflects very different rates of magma supply and lithospheric thickness beneath the ridge system. Only small sections, representing a fraction of the total crustal and shallow mantle stratigraphy in either environment, are presently available for study. Thus, models for accretion at slow- and fast-spreading ridges, and the state of the crust formed in these environments, remain largely a matter of speculation.

The lynch pin for interpretation of the nature and volume of the ocean crust for several decades has been the near layer cake seismic stratigraphy found throughout the ocean basins. This seismic stratigraphy has been equated to fundamental litho-stratigraphic breaks found in ophiolites, and has been used to extrapolate to the general crustal structure of the oceans. Until recently it was widely thought that seismic layer 3 marked the transition from intrusive gabbroic crust, formed as the fossil remains of magma chambers, to sheeted dikes which formed the feeder system to the overlying carapace of erupted basaltic lava. This interpretation was challenged, however, when drilling at 504B passed through seismic layer 3 without encountering gabbroic rocks. There, at least, seismic layer 3 coincides with an alteration front in the dikes. It is not known if this is the case elsewhere or coincidental to the Hole 504B section. Now the equivalency between the Mohorovicic seismic discontinuity and the igneous crust-mantle boundary is in question. Recent tabulations have shown that serpentinized mantle is far more abundant, and gabbroic rocks far less common in tectonic sections in slow-spread ocean crust than should be the case for a uniform 6-km crust. Some marine geologists now believe that the Moho may also be an alteration front - at least at slow-spreading ridges. This leaves estimates of the total igneous flux from mantle to crust over the last 300 Ma completely uncertain. The only way these major questions can be resolved is through deep ocean drilling.

Recent work has also shown that the biosphere extends to much greater depths than scientists initially thought (Parkes et al., 1994; Stetter, 1995) . As a consequence our present evaluation of the total earth biomass is likely to be significantly underestimated. A better evaluation of the total biomass is critical for several reasons including: estimates of oceanic and atmospheric CO_2 production, understanding the chemical environment of rocks and sediments and the chemical reactions occurring within them, understanding the food chain at the sediment-water, rock-water, and sediment-rock interfaces. There is also the likely possibility of discovering major new life forms previously unknown to science, as has already happened at ridge hydrothermal vents (e.g. the hyperthermophilic archaea — a whole new class of organism (Stetter, 1995). Questions as to how these organisms survive and thrive in these complex and seemingly hostile environments have potentially important technological and industrial implications. Evaluation of the biomass in the oceanic crust, however, requires a systematic approach to both drilling and on-site measurement of the organic content and properties of hard rock cores. Given the recent discoveries of diverse biotic communities living off heat from the earth's interior at ocean ridges, axial hydrothermal vent regions are particularly important to explore at depth in assessing total oceanic crust biomass.

Large igneous provinces (LIPs) are voluminous emplacements of mafic rock not clearly explained by the plate tectonics paradigm. LIPs provide the strongest evidence that at specific times in the past, energy transfer from the Earth's interior to its surface has occurred in a manner substantially different from modern processes. These provinces form the largest expressions of transient basaltic volcanism on Earth, and emplacement rates of the largest provinces may have exceeded the global integrated mid-ocean ridge production rate over time periods of roughly a million years. Moreover, LIPs may have been important contributors to crustal growth and continental stabilization throughout Earth history. Despite this, the evolution of large oceanic LIPs is poorly know. Largely covered by sediment, their timing and rate of growth must remain largely a matter of speculation without a systematic program of ocean drilling.

Although the progress in understanding convergent margins over the last 50 years is impressive, first order problems remain that are relevant to lithospheric formation. In the context of the oceanic lithosphere, of particular interest is the relationship between suprasubduction zone environments and ophiolites. Ophiolites, representing fossil oceanic crust formed in a rifting environment, are used as the major analog for the oceanic crust formed at ocean ridges. Yet many, if not most, ophiolites appear to have notable differences to what has been sampled *in situ* in the oceans. Do these differences represent a biased sample due to the limitations of surficial sampling, or do they reflect the differences between formation of ocean lithosphere above a subducting slab in a fore-arc or back-arc environment as many believe? What are the mantle dynamics associated with the transition from rifting to true ocean spreading in the back-arc environment? What processes operating in active convergent margins contribute to, or provide appropriate environments for, concentrating metals in massive sulfide deposits, particularly those which may be analogues for some of the larger, economically significant world-class precious and base metal deposits? Only deep ocean drilling can provide unambiguous answers to these critical questions.

Another major issue is the understanding of active processes at mid-ocean ridges which lead to the generation of the ocean crust. To decipher the mechanisms of oceanic accretion, it is essential to address their temporal variability. This can be done only with long term observation and measurement. Ocean drilling provides boreholes for *in situ* monitoring in order to document temporal changes in specific active processes. These are the necessary complement of the seafloor observatory that the InterRidge community wants to deploy on an active axial site.

Beyond the two COSOD meetings in 1981 and 1987, scientific planning of ocean lithosphere drilling up until now has largely been ad-hoc, based on proposals submitted by small groups of individuals with input from smaller working groups and USSAC supported meetings in the US (Coffin and Eldholm, 1990; Dick, 1989). There has been no formal integration with the various national ridge initiatives, though drilling is frequently mentioned in InterRidge and national ridge committee reports (Lin et al., 1994; Parsons et al., 1994). Thus, there has been no coordinated approach to planning utilization of scientific drilling vessels to accomplish InterRidge or LIPs objectives. Until now this ad-hoc approach has been sufficient due to the exploratory nature of ocean crust drilling. This exploratory phase is now largely over.

As stated in the ODP Long Range Plan (1996), the current phase of the Ocean Drilling Program (Phase II) extends through 1998. During Phase III (1999-2003), the *JOIDES Resolution* will continue to be the program primary drilling platform, although the use of alternate platforms to achieve specific objectives in particular environment, (i.e. shallow water, high latitudes, ...) will be considered. In 2003, the present Ocean Drilling Program will be over. Beyond 2003, ocean drilling will enter Phase IV. The scientific community expects a step in technology, to have access to deep-drilling (beyond 3000-m) that will open a completely new range of scientific goals. There is a Japanese proposal for a greatly improved ocean drill ship with riser capability (OD21) to be run by an international consortium successor to the present JOIDES structure. If the international scientific community wants this project - or an alternative one -to become a reality, it must begin the planning process and put serious scientific proposals for its use on the table. This is necessary (1) to demonstrate major international support for such a deep-drilling capability, (2) to guide the direction of the technological developments being planned so the future can meet the needs for the lithosphere community, and (3) because it is none too early to start the planning, site identification, and site survey process for drilling in the year 2003. Preparation of current ocean drilling legs can take 4 to 5 years, and identifying sites for total crustal penetration and their complete geological and geophysical characterization is likely to take even longer.

Given these constraints, the 100 scientists assembled in Woods Hole discussed the scientific goals that are listed in this report in the frame of a three phase approach. Phase II is almost over, since the planning is completed through 1998. It is imperative that there be a formal coordinated approach to identifying drilling strategies and targets to capitalize on the last 5 years of ODP, and to accomplish the highest scientific priorities during Phase III. Regarding Phase IV, this workshop represented the beginning of the planning effort for the ocean lithosphere community. As a whole, this report signals community wide support for Ocean Drilling Program through 2003 and for a new drilling program into the 21st century.

Henry JB Dick & Catherine Mével

2 - STEERING COMMITTEE REPORT

Introduction

Over 100 scientists attended the jointly sponsored ODP-InterRidge-IAVCEI Workshop: *The Ocean Lithosphere & Scientific Drilling into the 21st Century,* from May 26 to 28th, 1996 in Woods Hole Massachusetts. They considered current and past progress in understanding the evolution of the ocean lithosphere, along with the present and future need for scientific drilling in the oceans. The meeting represented the culmination of a series of meetings and workshops on the study of the evolution of the ocean lithosphere held over several years by both by InterRidge and the Commission on Large-Volume Basaltic Provinces (LIPs) of the International Association of Volcanology and Chemistry of the Earth's Interior (a member of the International Union of Geodesy and Geophysics). Thus, the recommendations presented here represent the considerations of a far larger group of scientists than those attending this one meeting.

The workshop participants emphasized that drilling is essential, in fact the only means, to provide continuous sampling and directly determine the stratigraphy of the oceanic lithosphere. Drilling is the only means by which geophysical interpretations can be ground-truthed, and to provide boreholes for *in situ* measurements and long term experiments in the ocean crust. It was recognized, however, that for the foreseeable future, drilling has to be focused, and must address the most important questions. Moreover, drilling legs must be part of larger integrated studies, involving other types of experiments organized in the framework of major global initiatives such as InterRidge, LIPs, MARGINS or the ION program.

To discuss scientific problems and set up specific experiments, the workshop participants split into 5 thematic working groups for detailed discussions and planning: 1) Fast-spreading Ridges; 2) Slow-spreading Ridges; 3) Active Ridge Processes; 4) Large Igneous Provinces; and 5) The Arc-Environment. While these groups fully covered the meeting mandate, it was felt that the inclusion of the arc-environment in this meeting was not widely known, and as a result the attendance for this group was too small to be representative of this scientific community. Thus, the steering committee feels that it can only point out areas where the interests of this meeting coincides with those of the convergent margins community, and recommends a more general workshop on convergent margins be convened, which includes these interests.

The meeting considered that the existence of a significant biomass within subseafloor rocks is a very significant discovery and represents a most exciting opportunity for science, which should be pursued with the utmost vigor. It recommends the formation of an ODP Detailed Planning Group to prepare for installation of a micro biological laboratory on the *JOIDES Resolution* as a matter of urgency and to make recommendations on the setting up of a Working Group on Biology. The meeting noted that InterRidge already has its own Biology Working Group (Co-Chairs D. Desbruyères and L. Mullineaux) which would be well-placed to assist ODP.

First-order scientific questions to be addressed

FAST-SPREADING RIDGES

Ocean crust generated at fast-spreading ridges covers over 50% of the surface of the planet. Although there is little direct constraint on its stratigraphy, geophysical experiments indicate that it is relatively homogenous in terms of crustal thickness and architecture. Unlike slower spreading ridges, there is also evidence from seismic refraction and reflection for a melt lens situated below layer 2, presumably at the dike-gabbro transition, implying a near steady-state geotherm in the zone of primary accretion. This, and radically different seafloor topography suggests that crust formed at fast- and slow-spreading ridges have a fundamentally different architecture. However, because of the lack of direct sampling, little is known of crustal accretion, dike injection, hydrothermal circulation, and lower crustal stratigraphy at fast-spreading ridges, or its relationship to seismic stratigraphy. The only means by which these fundamental questions can be directly addressed is by ocean drilling. This requires total penetration of the crust from the top of the extrusive basalt layer into the mantle in at least one location, as well as complementary drilling in a tectonic windows to address the lateral variability of the crust and shallow mantle at key stratigraphic intervals on the ridge segment scale. This mandates selection of an optimal site for total penetration in the near future, and devoting a number of legs to the same location over a relatively short period of time.

Because it is clear that reaching seismic layer 3 and ultimately the Moho will take years, and because the heterogeneity of the crust and shallow mantle on the local scale is unknown, the workshop participants feel strongly that the strategy of offset-drilling in tectonic windows should be pursued at Hess Deep, both to provide a partial composite section of fast-spread lower crust and upper mantle, and to explore its lateral variability in the three-dimensional framework of ridge segmentation.

SLOW-SPREADING RIDGES

As opposed to fast-spreading ridges, no evidence for a steady-state melt lens or magma chamber has been seismically determined at a slow-spreading ridge - except possibly beneath the Reykjanes Ridge, under the influence of the Icelandic hot spot (Sinha et al., 1997 ; Constable et al., in press). In addition, the igneous crust at slow spreading ridges has been determined by sampling and geophysical measurement to have highly variable thickness. Unlike the Pacific, the vertical stratigraphy of slow-spread lower crust has been directly constrained by drilling during ODP Legs 118 and 153 in the Indian and Atlantic oceans. These legs show that crustal accretion at slow-ridges reflects ephemeral magmatism, and deep seated deformation, hydrothermal alteration and tectonically controlled melt migration throughout the zone of crustal accretion. This has produced a complex vertical igneous, metamorphic and tectonic stratigraphy reflecting periodic migration of the zone of brittle-ductile deformation through the section in the absence of a steady-state geotherm.

Since Legs 118 and 153 recovered similar material, and as currently scheduled, Leg 176 will presumably provide a more fully representative section of the lower crust in one location, the workshop focused on how to understand the processes which led to the vertical heterogeneity and how to explore its lateral variability on the scale of a single ridge segment. The workshop proposes two drilling experiments on the Mid-Atlantic Ridge to determine (A) the structure and composition of the crustal component of slow-spreading oceanic lithosphere and its evolution in time, and (B) the along-axis chemical, lithologic, and structural variations in the uppermost mantle at the ridge segment scale, and its relation to crustal accretion. The drilling experiments will focus effort on crustal variation along a “normal” segment of northern Mid-Atlantic Ridge and on an “end-member” area to the south, where partially serpentinized peridotites crop out on the flank of the rift valley wall along the length of several spreading segments. These experiments will allow us to directly constrain the nature of the whole system of melt migration, mantle flow and crustal accretion at the critical ridge segment scale for slow-spreading ridges. They will determine the lithology of the geophysically defined crust, and will show the extent and nature of its variability along a spreading segment and how it evolves with age.

ACTIVE PROCESSES

Active processes, hydrothermal, magmatic and tectonic, occur in a variety of environments on the seafloor. A key parameter for understanding these processes is gaining insight into their temporal variability. Monitoring of active processes requires seafloor observatories to which drilling will contribute by allowing borehole instrumentation and long term measurements. Among all the possible options, highest priority is given to the ridge axis. This involves drilling and instrumenting 5 boreholes in conjunction with a ridge axis observatory experiment. The ideal configuration would consist of 4 holes to ~500-m depth and 1 hole to ~2-km depth, distributed in an L-shaped array. All five holes would be logged, CORKed and instrumented in order to determine the physico-chemical state of the crust in the region of an active volcano-hydrothermal system and to monitor fluid and geochemical evolution of the hydrothermal system over decade time scales.

Since this experiment must rely on the further development of current technologies such as DCS and the hammer-in-casing, other critical environments should be also considered for Phase III drilling. These include the area of the experiment initiated on the flank of the Juan de Fuca Ridge (leg 168), as well as mid-plate volcano and convergent margin hydrothermal systems.

LARGE IGNEOUS PROVINCES

The Cretaceous period is marked by voluminous and episodic basaltic magmatic events that are not clearly associated with plate tectonic processes: approximately twenty oceanic plateaus, volcanic passive margins, and continental flood basalts were emplaced during that period of time. Through ocean drilling, we seek to better understand the timing, genesis and environmental effect of voluminous mafic magmatism. For this, we must determine the chronology of individual LIP emplacements as well as that of all LIPs during the entire Cretaceous period. Determination of source composition, melting regime, and melt migration is critical for understanding asthenospheric and lithospheric geodynamic processes. The tectonic setting and deformational history of LIP emplacement must be defined so that the interaction between LIPs and plate tectonics can be better understood. Finally, the impact of Cretaceous LIP emplacements on the biosphere, hydrosphere, and atmosphere is potentially highly significant and should be fully investigated.

Two of these LIPs, Ontong Java and Kerguelen plateaus, are giants, each covering an area of ~2 x 10^6-km^2. To meet our scientific objectives, exploratory drilling and associated geophysical investigations of these two features are given the highest priority. In addition, other members of the Cretaceous LIPs family, both older and younger, must be surveyed and drilled to address key LIP issues. The necessity of appropriate crustal and mantle geophysical surveys on Cretaceous LIPs must be emphasized; integration of these geophysical data and drilling results is critical to addressing fundamental LIP science objectives. Eventually, at least one deep hole should be drilled in one of the LIPs.

THE ARC ENVIRONMENT

Since the arc environment working group did not feel it could represent their entire community, they focused their discussions on two major problems associated with the oceanic lithosphere.

The first of these is testing the ophiolite model. Although ophiolites are often considered as ancient analogs to oceanic crust, much evidence suggests that many actually formed in a supra-subduction zone environment. Fore-arcs are the best candidates to explain most of the features observed in these ophiolites. Deepening a hole in a fore-arc to the plutonic section will provide a reference section to test this model, and provide a means for evaluating the extent to which they can, or should, be used as direct analogues for crustal formation at mid-ocean ridges.

Secondly, most of ore deposits of great economic importance were not formed in large ocean basins - but in oceanic crust in the arc-environment, formed in association with the rifting of continental or newly formed arc crust. Drilling one of these deposits *in situ* (possibly Pacmanus in the western Pacific) will help understanding hydrothermal processes and the formation of large ore bodies.

Implementation

Implementation is discussed as a two stage approach: before and beyond 2003 (Table 1). Until 2003, the *JOIDES Resolution* will remain the primary drilling platform of ODP. Individual legs identified and proposed for the period 1998-2003 (end of Phase II, Phase III) in this scheme reflect the discussions within the 5 working groups. Each group focused on the minimum number of legs needed to meet their highest priorities. Although no general prioritization is made among these legs, four of the groups identified their highest priority and these were endorsed by the meeting-at-large. The arc-environment group proposed two legs, which they did not prioritize, but were endorsed by the workshop at-large for further consideration by the active margins community. The total number of legs proposed probably exceeds what can reasonably be expected within the 2003 time frame, but we are aware that the scheduling of a leg is dependent on a number of considerations, including logistical constraints and proposal readiness, and thus, some are unlikely to be drilled prior to 2003 for these reasons. Beyond 2003, the future configuration of ocean drilling is still poorly constrained and so the report focuses on the general directions which drilling should pursue.

BEFORE 2003: END OF PHASE II AND PHASE III OF THE OCEAN DRILLING PROGRAM

Phase II of the ODP Long Range Plan is almost at an end. Several of the currently scheduled legs will address this workshops objectives. Leg 176 will deepen Hole 735B near the SW Indian Ridge to close to 2-km in slow-spread lower crust at the end of 1997, and Leg 183 has now been scheduled to drill the first leg of the proposed two-leg Kerguelen program in 1998. In addition, Leg 179 is scheduled to test the hammer-drill in casing system at Site 735.

During Phase III, we expect to continue using the *JOIDES Resolution*. After careful consideration of the limited time available, experiments were designed which could best address the present gaps in our knowledge of the ocean lithosphere.

On mid-ocean ridges, the major gaps to fill include: A) The shallow and intermediate depth crustal structure of fast-spread oceanic crust, about which almost nothing is known, and the completion of a composite vertical section of tectonically exposed fast-spread lower crust and mantle at Hess Deep using offset section drilling; and (B) The lateral heterogeneity of the crust and shallow mantle at slow-spreading ocean ridges (believed to be more extreme than in the Pacific).

In order to reach intermediate crustal depths (~3-km) in old Pacific crust by the end of Phase III, an exploratory drilling leg should be devoted as soon as possible (1999) to locating a site for this deep hole. This site should then be re-occupied and a new hole, designed for deep penetration should be drilled through the dike-gabbro transition by the end of the Phase III (2-3 legs). An important objective of this hole is to extend ODP's limited experience with deep crustal drilling and to locate the initial site for drilling to the MOHO during Phase IV. If the initial attempt to locate a site for deep-drilling in the Pacific fails, given the difficulties already encountered in drilling Pacific crust, it is proposed that ODP and InterRidge fall back to Site 504 on intermediate-rate crust where the crustal structure is already well characterized and we know good drilling conditions exist. In this option, ODP would abandon the existing deep hole due to its distressed state, and redrill and case most of the Hole 504B section, coring ahead from that point down to several hundred meters below the dike-gabbro transition. In addition, by the end of the present circumnavigation of the Resolution from the Atlantic through the Pacific, the second Leg of Hess Deep drilling must be accomplished as well. Proposals for neither of these experiments, or the backup program at Site 504, presently exist beyond this report, and these must be put into the ODP-review process as soon as possible for this to happen.

This report endorses and extends the two InterRidge experiments designed to address lateral crustal and mantle variability in the Atlantic. One is an array of shallow holes in crust at the center and the end of a single spreading segment. The location of this experiment is still to be determined. Two of these shallow holes would be later selected, on the basis of drilling conditions and segment position, for deepening during a follow up leg later in the cycle before the ship leaves the Atlantic in the 2000-2001 time period. The experiment to study shallow mantle flow, lateral mantle heterogeneity and melt-transport at the rift segment scale requires a single leg to drill an array of ridge-parallel shallow holes in a belt of partially serpentinized peridotites situated along the rift valley wall at 15°N. Again, proposals for the two Atlantic experiments do not presently exist in the ODP review system, and must be prepared soon, if this program is to proceed.

The highest priority for LIPs in Phase III is to drill the Ontong Java plateau, which will complete the initial exploration of the two giant Cretaceous large igneous provinces. In addition, given their inherent complexity, drilling significantly older and younger LIPs is needed in order to obtain a temporal perspective on deep mantle circulation and the formation of large igneous provinces. At this time, proposals for Ontong Java, Caribbean, Shatsky Rise, and a NW Australia LIP exist within ODP. Thus, this community is well positioned to move ahead with its program, though ODP should formally identify a working group or PPG to liaison with SCICOM. We note that such a group (commission) already exists under the IAVCEI umbrella and only needs to be partially co-opted by the ODP structure for this purpose.

The ridge axis seafloor observatory proposed by the workshop will involve drilling 500-m deep holes in very young near zero-age crust. Given past drilling experience, this requires the improvement of current drilling technologies for the *JOIDES Resolution* (hammer-drill, DCS), and thus, should be tentatively planned for in the latter half of Phase III. If the technology does not become available, then a program in less technologically challenging environments should be considered, such as continuing the ridge flank experiment initiated on the Juan de Fuca. In addition, a second priority, to drill a convergent margin hydrothermal deposit with the existing Resolution technology does not need to wait for these improvements and can be done early in Phase III.

PHASE IV - POST 2003

Phase IV will require the use of another platform with deep-drilling capabilities. The first priority will be to achieve total crustal penetration through MOHO in fast-spread crust. At the MAR, the two intermediate depth holes from Phase III should be deepened to achieve crustal penetration. One deep hole, and possibly two intermediate holes should be drilled in a LIP. This deep-drilling will require large amounts of drilling time.

In the framework of a two ship program, the lithosphere community needs continued access to a ship with drilling capabilities similar to the present *JOIDES Resolution* for many of the programs initiated during Phase III, and for new projects. Much of this is likely to focus on intraplate volcanoes, offset drilling in tectonic windows in various settings to explore the lateral heterogeneity of the ocean lithosphere, and to fully investigate the arc environment. An important role of this ship will also include servicing, extending and new construction of seafloor observatories, as well as deploying instruments for long term observation.

TECHNOLOGICAL REQUIREMENTS

The workshop participants felt that the capability of the *JOIDES Resolution,* using present drilling technology, for drilling deeper holes (up to 3-km or more subseafloor) in oceanic crust has not been fully exploited. Therefore, the lithospheric drilling objective defined for Phase II and III seem to be achievable with the *JOIDES Resolution*.

However, during these two phases, it is essential to improve penetration and recovery. The hammer-drill-in-casing system is a great hope for starting holes on slopes in unstable young crust. The DCS is necessary to drill holes to 500-m at ridge axis to monitor active processes. This will also require a new generation of borehole instrumentation and logging tools designed to measure the physical and chemical properties (e.g. CORKs for slim holes produced by DCS).

There is very strong interest in the ocean lithosphere community for drilling a few very deep holes (up to 6-km or more subseafloor). A ship equipped with a riser would be a great help for drilling deep holes. However, many the lithospheric drilling objectives are beyond the reach of a riser with a 2500-m water depth capability, which seems to be the limit, at this time, for a conventional riser. To meet the need of this community, the objective is to drill in 4000-m water depth. If a conventional riser cannot meet this objective, other directions should be explored, such as “riserless drilling” or slim line riser.

Exploring the deep biosphere is a common interest to all the thematic groups and is a very exciting and almost entirely new field. However, there are still technological problems to solve to address this new question. In particular, tools to sample the biota without contamination need to be developed, and a biology laboratory needs to be designed and installed on the Resolution as soon as possible.

RECOMMENDATIONS FOR PLANNING GROUPS

The conference heard that ODP is in the process of reorganizing itself, and would replace the science planning aspects of the existing Planning Committee (PCOM) by a new Science Committee (SCICOM). This committee would consider proposals in accordance with the Long Range Plan objectives and may also seek advice directly from working groups set up for major ODP scientific themes. The Workshop, recognizing that all proposals will be graded for scientific merit by independent scientific review panels, and therefore must compete on merit, felt it obvious that working groups would be critical to insure the sustained focused and coordinated effort required to accomplish major multi-leg or long-term scientific projects. As they saw it, such working groups would have the responsibility for soliciting, and possibly writing, proposals, and forging them into practical drilling plans for presentation to SCICOM.

The conference recommended that ODP set up four working groups (PPGs as SCICOM has now designated them) in its areas of interest, noting that only 2 of these solely represents the ocean lithosphere community, while the others overlap with a broader scientific community.

RIDGES PPG

Roger Searle as Chair of InterRidge was charged with presenting ODP PCOM with nominations for a Ridges PPG, in consultation with the InterRidge Steering Committee. It is anticipated that the PPG will have the responsibility for soliciting, and possibly writing, proposals, and forging them into a single practical drilling plan for presentation to SCICOM, to cover both fast- and slow-spreading (or ‘hot’ and ‘cold’) ridges. A group of some 16-20 nominations should be put forward, representing people who would take a vigorous interest in preparing and promoting the drilling plan. Nominees should include representatives of the main projects conceived at this (Woods Hole) meeting, and two liaisons from InterRidge. InterRidge should also reserve the right to add or replace members as appropriate in consultation with SCICOM. The nominations should include 3-4 potential candidates for chairing the group.

LARGE IGNEOUS PROVINCES PPG

Similarly, Mike Coffin as Chair of the IAVCEI LIPs committee was charged with presenting PCOM with nominations for a LIPs PPG.

ACTIVE PROCESSES PPG

There should be a PPG on Active Processes that would cover hydrothermal venting, cold seeps, borehole instrumentation and seafloor observatories. It is suggested that this group have joint membership from the InterRidge, ION and MARGINS programs. The InterRidge Steering Committee is asked to consider, together with ION and MARGINS, how best to set up this Group, and to make suitable recommendations to PCOM.

BIOLOGY PPG

The meeting considered that the existence of a significant biomass within subseafloor rocks is a very significant discovery, representing a most exciting opportunity for science, which should be pursued with the utmost vigor. It recommends the formation of an ODP Detailed Planning Group to prepare for installation of a micro biological laboratory on the *JOIDES Resolution* as a matter of urgency and to make recommendations on the setting up of a PPG on Biology. The meeting noted that InterRidge already has its own Biology Working Group (Co-Chairs D. Desbruyères and L. Mullineaux) which would be well-placed to assist ODP in setting up its own.

ACTIVE MARGINS

The workshop participants considered drilling in active margins in the context of the broader question of the evolution of ocean lithosphere, and not in the holistic sense of the back-arc - volcanic arc - fore arc - fore arc basin -accretionary wedge system overlying active subduction of oceanic crust. Accordingly, we have endorsed specific drilling projects, but believe these should be considered in a broader context by a more representative body of scientists focused on the active margins environment. It is this latter group from which any recommendations for active margins working groups should come.

Post-cruise science and site survey requirements

A concern of the workshop participants is the lack of post-cruise science support funds for ocean drilling. Given the total investment these cruises represent, available funding to study the cores and data in many partner countries are seriously inadequate. If the Ocean Drilling Program is to be successful in realizing its ambitious goals, then this will only be realized if funds are adequate to support major scientific studies of the material through to publication in peer-reviewed international journals for each leg of ocean drilling. Under the present funding mechanisms, this is rarely the case in the US and in other partner countries. This, in good part, accounts for the lack of a commensurate community awareness of the success of the Ocean Drilling Program outside the drilling community itself and those who read the ODP Proceedings Volumes. Moreover, given the geriatric nature of cores, which degrade rapidly after they are collected, both through sampling and exposure to surface conditions, the inadequacy of post-cruise funding represents a significant loss of the scientific opportunity afforded by scientific ocean drilling, since this research cannot be postponed indefinitely.

A second concern of the workshop is that with the change in the Ocean Drilling Program to more focused long range planning with the formation of project specific working groups, a new approach to site survey funding is required. In the current system, dedicated funds for routine site surveys of major drilling targets are not available, either through Co-mingled funds or in most of the partner countries. As a consequence, site surveys, which often represent routine data collection, are forced to compete directly with cutting edge stand-alone scientific programs. In some cases, funding agencies have refused to consider drilling and survey as an integrated scientific program, even where the drilling is scheduled. Thus, a survey proposal which represents a major part of a highly ranked first-order scientific program of integrated drilling and survey, may be down-graded to an unfundable ranking as a stand-alone-program. In other cases, sufficient funds are not available in a partner country to fully fund a single site survey, where such a program could be mounted if several countries were able to pool their resources. However, this has proved difficult with the different funding mechanisms, review processes, and deadlines of the various national funding agencies. Thus, we recommend that ODP Council consider these problems and make a collective recommendation to the agencies they represent, in order to facilitate the funding of dedicated site surveys, without which the new long range planning efforts of ODP cannot succeed.

3 - TECHNOLOGICAL REQUIREMENTS FOR OCEAN LITHOSPHERE DRILLING

Introduction

Technological innovation and long-term scientific goals are closely linked for ocean lithosphere drilling. From the discussions within the five working groups at this meeting a consensus was developed on three major points regarding the future technological needs for lithospheric drilling:

- **for the foreseeable future many lithospheric drilling objectives on LIPs, in arc settings, and in oceanic crust can be achieved with the technical capabilities of the present *JOIDES Resolution***
- **the capability of the *JOIDES Resolution,* using present drilling technology, for drilling deeper holes (up to 3-km or more subseafloor) in oceanic crust has not been fully exploited**
- **there is very strong interest in the ocean lithosphere community for drilling a few very deep holes (up to 6-km or more subseafloor) and for drilling in young, unsedimented oceanic crust, neither of which are feasible with the drilling technology currently available to ODP**

The following sections outline the specific technological and facility needs for lithospheric drilling in both the short term (Phase III of the present program: 1998-2002), and in the longer term (2003 and beyond).

The years 1998-2002, Phase III of ODP

During this phase of ODP, many lithospheric drilling objectives can be addressed with the technical capabilities of the present *JOIDES Resolution*. For example, the offset drilling strategy employed successfully at Hole 735B, in Hess Deep, and at MARK can continue to be used to sample different crustal levels and to investigate the geologic nature of major seismic boundaries such as the layer 2/3 transition and Moho. Relatively shallow basement holes can also be used to map the age distribution and composition of volcanics forming LIPs and to investigate the variation in upper oceanic crustal structure and its relationship to age or ridge segmentation. However, during this phase of the program it is essential that existing drilling technology be improved in two ways: (1) we must obtain the ability to drill successfully in young, unsedimented oceanic crust, and (2) we must explore the limits of existing riserless, deep water drilling technology to drill deep holes into oceanic crust.

Studies of the magmatic, tectonic, hydrothermal and biological processes which accompany the formation of oceanic crust require the ability to drill holes in young, unsedimented, highly fractured and hot oceanic crust. ODP has two very promising ongoing development efforts that should receive a very high priority in this phase of the program. The first is **hammer-drill-in-casing**, which will be tested on Leg 179 in mid-1998. By casing the hole in the highly fractured, unstable, uppermost crust while drilling it may be possible to overcome the hole collapse problems which have severely limited pervious efforts in this setting. The second critical technology for young crustal drilling is the DCS which has been under development within ODP for more than a decade. DCS offers the potential for higher penetration rates, greater hole stability, and higher recovery rates than with conventional rotary drilling. Demonstrating the feasibility of DCS drilling in oceanic crust in this phase of the program is essential for achieving many longer term lithospheric scientific goals.

There was a broad consensus at the workshop that the potential of the present drill ship for drilling deeper holes has not been fully exploited and that a major goal of ODP in the 1998-2002 time frame should be drilling one hole in the Pacific to a depth of at least 3-km into the crust. With a "workable" drill string length of 7 to 7.5-km, the *JOIDES Resolution* is capable of drilling 3-km into the oceanic crust in water depths of up to 4000 m. The key to successfully deep-drilling is hole stability and reducing thermal stresses on the hole. Hole instability can arise from natural causes such as faults or induced factors such as borehole breakouts, thermofractures, and pipe wear. ODP has the ability, which so far it has not had an opportunity to use, to set telescopic casing and thus, case a deep hole to a substantial depth. This will not only help stabilize the hole but will also facilitate removal of cuttings. To avoid crustal temperatures in excess of 300°C, and to minimize thermal stresses, a 3-km deep crustal hole should be drilled on seafloor at least 10 Ma old, preferably older. Thermal stresses can also be reduced by using mud continuously in the hole, keeping the mud in the hole and minimizing fluid circulation (outside of coring operations). With this approach, a 3-km deep hole in oceanic crust could potentially be drilled, cored and logged in 3-4 legs with existing technology. Indeed, the main impediment to such a hole is political, not technological - selling the broader ODP community on the value of devoting 3-4 legs of drilling to a single hole.

The year 2003 and beyond, Phase IV of ODP

The ODP Long Range Plan calls for a two-ship program in the post-2003 period - a deep water riser vessel and a second ship with capabilities comparable to the present *JOIDES Resolution.* **The workshop endorsed the concept of a two ship program for post-2003. Future lithospheric drilling objectives will require *both* the capabilities of a *JOIDES Resolution*-type vessel and a deep-drilling ship**. There was also a clear recognition, given the very diverse scientific interests within the international ocean drilling community and the substantial amounts of time required to drill deep holes, that deep-drilling into oceanic crust would be politically feasible only within the context of a two-ship program.

There was, however, considerable debate at the workshop regarding the deep water, conventional riser ship proposed by OD-21 and its ability to address some of the lithospheric scientific objectives identified at this workshop. A riser drilling system is clearly needed for certain kinds of ocean drilling. For example, it is a necessity for drilling in sedimentary sections where there is significant risk of encountering oil or gas. Riser drilling in rapidly deposited, thick sedimentary sequences along rifted margins or in porous, deforming sedimentary wedges above subducting slabs may also improve core recovery and depth of penetration, as well as permit installation of instrumentation for post-drilling monitoring. However, there are two fundamental concerns with using conventional riser technology for attacking some crustal drilling objectives. The first problem is the potential depth limitation of a conventional riser. Industry is routinely using this technology in water depths of <1000 m; the longest riser systems in use today are approximately 2000 m. Many experts in industry believe these systems are pushing the very limits of this technology and industry is actively exploring several alternatives for drilling in deeper water including using risers made out of high-strength composite materials, slim line risers, bottom-positioned risers, and deep water "riserless" drilling.

The OD-21 vessel is being proposed with a 2500-m conventional riser system in 2003, with the possibility that this may be upgraded to ~4000-m by the year 2007. The 2500-m riser system will not be able to address many of the highest priority scientific objectives identified for ocean crustal drilling. Nearly all oceanic crust lies in water depths greater than 2500-m. Moreover, because of the high heat flow in young lithosphere, deep holes will have to be drilled well out on the ridge flanks. For example, in order to keep borehole temperatures less than 300°C throughout the crust (a practical upper temperature limit for drilling and logging), deep holes will have to be located on seafloor >30 Ma old. This corresponds to water depths of ~4500-m or greater. These depths are well beyond the capabilities of the 2500-m riser system proposed for the OD-21 vessel. **Even if a 4000-m riser system proves technically feasible (and a 4000-m system is well beyond anything industry has built to this date), such a system will not be capable of drilling in much of the older ocean basins and may not be ideally suited for drilling to Moho in normal oceanic crust because of the high temperatures that will be encountered in the lower crust in young lithosphere.**

A second concern with using conventional riser technology for deep crustal drilling is that it does not directly address the problem of thermal stress-induced hole instability. It has been suggested that at Hole 504B the circulation of cold sea water in the hole is a major cause of hole instability — each °C of cooling at 2000 mbsf generates a thermal stress of about 0.8 MPa. A cooling of 100°C can result in a total effective stress reduction of over 80%. In conventional riser drilling, rapid circulation of drilling mud through the hole is used to remove cuttings, but this may result in large thermal stresses on the deeper sections of the hole leading to hole collapse. If this is actually a major problem, then to minimize thermal stress-induced hole instability, it will be necessary to keep the temperature difference between the hole walls and the drilling mud to less than 50°C. Locating drilling sites on comparatively old crust will help, but a modified strategy for minimizing fluid circulation in the hole is also needed.

It should be noted, however, that caliper logs of Hole 504B show that there are many large breakouts, creating cavities within the hole and around the short section of casing at its top which make it difficult to pump cuttings out of a 2-km deep hole. Since the drill string stuck most often when rotation and pumping stopped to recover core, it is likely that the principle problem in continued drilling there is cuttings falling back around the string, causing it to jam and stick when rotation is resumed after retrieving a core. This problem would be alleviated by redrilling a new hole and properly casing it down close to the present depth, and then resuming coring on down to greater depth.

Given the above concerns, the workshop strongly recommends that alternatives to conventional riser drilling technology be investigated for deep water, ocean crustal drilling. One such option is deep water "riserless" drilling (Figs. 7 and 8). Another is a hybrid system — a shallow water riser system (perhaps limited to depths of 1000 m) coupled with a deep water system using slim line or riserless technology. Industry has a strong interest in developing new deep water drilling technology — experts estimate that by the year 2000 they will be drilling in 12000 ft of water (~4000 m) in the Gulf of Mexico. **ODP should take advantage of the expertise and technology developed in industry for deep water drilling as it weighs the options for deep ocean scientific drilling in the post-2003 period.**

4 - WORKING GROUP REPORTS

4.1 - FAST-SPREADING OCEAN RIDGES WORKING GROUP REPORT

Lithospheric Architecture and Aging at Fast-spreading Ridges

Participants: Rodey Batiza (chair), James H. Natland, Stanley R. Hart, D. Jay Miller, James Allan, Ingo Grevemeyer, Craig Manning, Ralph Stephen, Phillipe Pezard,

Summary

Our charge was how best to approach understanding the architecture and aging of crust formed at fast-spreading ridges using drilling, including deep-drilling without well control before the year 2003, and with well control after that. Fast-spreading ridges were identified by the workshop Steering Committee as an important and characteristic type of ridge, particularly in terms of geomorphology, seismic structure, and axial processes, that might be useful to treat as an entity or end-member in defining goals for future drilling. The flanks of such ridges have been little studied by drilling, in part because it has proven extremely difficult to penetrate surficial fractured basalts by rotary coring. The extent of these difficulties requires careful thought in development of any strategy for future drilling of this type of crust.

Our working group, thus, considered the general problem of drilling of crust produced at fast-spreading ridges from two perspectives. What are the scientific objectives of such drilling? And how can we get to the point of deciding that drilling long sections past surficial basalts is feasible? We also had to decide just how much might be learned from the alternative strategy of offset-section drilling, for which a start has already been made at Hess Deep during ODP Leg 147.

The following strategy was decided upon: We propose that there should first be one leg of exploratory drilling in older crust in the eastern Pacific, when *JOIDES Resolution* returns to the Pacific in 1999, to determine how, or if at all, we might be able to establish a deep hole, comparable to Hole 504B on the Costa Rica Rift, in fast-spread crust. Preliminary information is presented below on two general regions where this drilling might be attempted. Success in this venture is defined as leaving an open re-entry hole penetrating at least 300-m into basalts. If such a hole can be started, additional legs can be planned to drill it without a riser to 3-km by the year 2003 (End of Phase III of the Long-Range Plan), casing it to perhaps 2-km, and then extending it to the mantle, presumably using riser drilling, after that. The overall scientific objective prior to 2003 is to drill through basalts and sheeted dikes far enough into gabbros to penetrate beyond the zone of crust once occupied by a melt lens at a ridge axis. Three kilometers should be sufficient to do this. However, if the exploratory leg proves unsuccessful, we propose, as an alternate, drilling a 3-km hole next to Hole 504B for the same purposes, although the Costa Rift has only a medium spreading rate. The seismic structure in the vicinity of Hole 504B is very well known. Eventual penetration into the mantle there might be possible because the crust is only 4.5-km thick, and we already know we can drill to a depth of 2-km; we need no more exploratory drilling. Many of the objectives of understanding crustal architecture can, thus, be addressed near Hole 504B, and it is a viable fall-back if we cannot get started on fast-spread crust. A single deep hole, however, fails to address the key issue of the lateral variability of the lower ocean crust and shallow mantle. While we anticipate that the crust is likely to be relatively uniform in composition and structure at fast spreading ridges, we see a clear need to address this question. To do this we advocate one leg of additional offset-section drilling at Hess Deep before the year 2003, to explore the three-dimensional diversity of the lower crust and the crust-mantle transition.

Scientific Rationale

Although fast-spreading ridges represent only about 20% of the global ridge system, they produce more than half of the ocean crust on the surface of the planet, almost all of it along the East Pacific Rise. Most ocean crust currently being recycled back into the mantle at subduction zones was produced at a fast-spreading ridge. If we wish to understand the Wilson cycle in its most typical and geodynamically significant form, we need to examine ocean crust produced at fast-spreading ridges.

In the past twenty years, the East Pacific Rise has been sufficiently probed and prodded to provide a first-order outline of its structure, segmentation, magmatism, petrology, and hydrothermal activity. The dimensions of axial magma chambers, once thought to be huge, are now considered to be quite small, no larger than about a kilometer or two in width and perhaps 50 meters thick, as defined precisely by the ubiquitous reflectors seen at about 1.5 kilometers depth on multi-channel seismic profiles across and along the Rise axis. Although similar reflectors have been mapped along some other more slowly spreading ridges, it is still fair to say that they are best expressed and most widely present along the East Pacific Rise.

The melt lenses defined by the reflectors are interpreted by seismologists to occur immediately beneath the base of sheeted dikes which feed eruptions in an extremely narrow neovolcanic zone, oftimes delimited by a small, fissured, rift graben along the axial summit. Since this is also the location of almost all of the high-temperature hydrothermal vents along the East Pacific Rise, there is an obvious, but as yet poorly understood relationship between hydrothermal circulation and its associated mineralization, dike injection, and the freezing of melt in the lower crust. The role of the melt lens in all of this is speculative, but it is clearly crucial. The source of the mineralizing fluids is sea water that has reacted extensively with the crust, inducing metamorphic transformations of rock somewhere above the melt lenses, and carrying soluble components of the rocks to the seafloor. The vigor and extent of hydrothermal action along the East Pacific Rise, with rapidly venting hot smokers spaced regularly along the neovolcanic zones, also suggests that there is, at least for a time, a highly porous and permeable zone of fractured rock aligned directly above the melt lens, through which hot fluids may jet. Approximately one third of the total heat flux involved in cooling of the oceanic lithosphere occurs in this way.

At this stage, to ground truth all the interpretations derived from indirect measurements, it is essential to drill. Drilling will address four broad themes: 1) linking seismic stratigraphy to lithostratigraphy; 2) geochemical characterization of large- and small-scale lithologic units; 3) vertical and temporal evolution of ocean crust, including definition of zones of hydrothermal and magmatic chemical exchange; and 4) physical properties of the ocean crust. As a start, a borehole should penetrate through the upper crust and the sheeted dike complex and into gabbro produced both at the level of the melt lens that lay beneath the spreading ridge and the complex gabbro sequence produced by crystallization of the transition zone of partial melt (the mush zone) beneath. At the same time, a leg should be devoted to drilling in a tectonically exposed section to test the lateral heterogeneity of the lower crust and mantle. Ultimately, when very deep-drilling (>3-km) becomes available to the scientific community, the goal is to drill the lower crust and through the seismically defined Moho to ground truth its petrological significance in a fast-spreading environment: transition between the magmatic crust and residual mantle ?

1) LINKING SEISMIC STRATIGRAPHY TO LITHOSTRATIGRAPHY.

Coring a continuous section through the basalt pile, the sheeted dike complex, and ultimately into mid-crustal gabbros, will provide the necessary field evidence to calibrate geophysical models of the ocean crust. We see this course as being ideally suited to fast-spreading crust in the Pacific, as models for its' seismic stratigraphy are simple and uniform, lacking the level of complexity inherent in the seismic structure of slow-spreading ocean crust. A long-standing goal of ocean drilling has been to define the lithologic correlation with seismic boundaries, particularly the layer 2/3 seismic boundary. Recent geophysical evidence has refined our models of ridge crustal structure with the hypothesis of long-lived, thin (>1-km) lenses of magma underlain by a much thicker, broader zone of semi-coherent crystalline rock with a few percent melt- filled porosity (the !mush zone!). This image of the crust is not seismically resolved off-axis, once crystallization of the melt is complete. A primary goal of a 3-km hole is to recover and identify zones of gabbro that originate from these two seismically-defined intervals. Additionally we hope to focus on how melt is transported through the mush zone and into the magma lens, with subsequent transfer through conduits to the upper crust. Additional evidence from recent drilling at Hole 504B suggest that the layer 2/3 boundary, as defined by an increase in seismic velocity, does not represent the transition from sheeted dikes to gabbro but rather reflects the filling of primary and secondary porosity by metamorphic minerals precipitated by hydrothermal circulation. A fundamental goal of this drilling, therefore, is to determine the nature of the transition from layer 2 velocities to layer 3 velocities. With a judiciously chosen target, we can also investigate the hypothesis deduced from seismic experiments that fluid-rock interactions generally cease in crust more than 30 million years old.

2) GEOCHEMICAL CHARACTERIZATION OF LARGE- AND SMALL-SCALE LITHOLOGIC UNITS IN FAST-SPREAD CRUST

ODP Leg 147 cored a short 154-m section of high-level gabbros in an isolated tectonically disrupted block at Hess Deep in the Pacific (Gillis et al., 1993). These were originally emplaced beneath the East Pacific Rise, and their petrology suggests that they originated in a crystal mush zone below the sheeted dikes, reflecting a complex igneous and metamorphic paragenesis - including several different mechanisms of melt transport (Natland et al., 1991; Pedersen et al., 1996). A notable finding, contradicting what has generally been assumed, is that the melt lens may not be the primary source of erupted MORB along the EPR, but rather represent a stagnation point for highly fractionated silicic melts beneath the sheeted dikes (Natland et al., 1991). Definitive interpretation of the physical and chemical evolution of even a significant portion of the lower crust from such a short section is difficult, however, and requires considerable inference. Only sampling a continuous section through the extrusives, dikes and underlying gabbros will provide the key stratigraphic relationships required to do this. Such a hole will provide the opportunity to establish the petrophysical and geochemical continuity between extrusive basalts, dikes, and the lower crust. This will allow identification and study of the accretionary processes by which the lower crust is formed, the nature of the magmas in the melt lens, what controls melt evolution and the means by which they are transported through in the lower crust. Most importantly, it is the only means by which the composition, internal stratigraphy and state of alteration of fast spread lower ocean crust can be determined.

3) EVOLUTION OF OCEAN CRUST

We know that profound changes occur in the physical and chemical characteristics of oceanic crust as it ages. The best known manifestation of these processes is the doubling of compressional wave velocities in the upper crust from about 2.5-km/s at zero age to over 4-km/s in mature crust. Our knowledge of the structure of the uppermost crust and the processes that cause and control this evolution and alteration is inadequate: insufficient data exist to satisfactorily constrain quantitative models of the physical and chemical processes that produce these large and apparently systematic changes in about 60% of the hard rock surface of the earth. Sampling this section will allow us to investigate the alteration profile in off-axis crust and compare it with models of crustal evolution (e.g. the ophiolite model of alteration processes).

Mechanisms of hydrothermal fluid transport and alteration in the deep ocean crust have yet to be well characterized. Defining the depth of penetration of sea water into the crust requires petrographic and geochemical analyses (e.g., d^{18}O) of a long continuous *in situ* section of ocean crust and cannot be indirectly inferred by remote sensing or from ophiolites of ambiguous geologic setting. The initial results from drilling suggests large differences in the character of alteration with spreading rate. The short 154-m Hole 894G gabbro section from Hess Deep suggests that an off-axis cracking front plays the major role in circulation of sea-water at high temperatures into the lower ocean crust formed at fast-spreading ridges (Manning and MacLeod, 1996). By contrast, at slow-spreading ridges the results from the 500-m Hole 735B gabbro section suggests that alteration and hydrothermal fluid circulation at high temperature occurred beneath the ridge axis, controlled by lower crustal shear zones (Dick, 1991; Mével and Cannat, 1991; Stakes et al., 1991). Only deep representative sections drilled in gabbros at fast-spreading ridges can actually resolve whether this difference on the controls on high-temperature circulation with spreading rate is real.

A continuous hole into the lower crust will allow *in situ* sampling of deep crustal fluids. Determining whether these fluids are modified sea water, conjugate phase-separated brine and vapor, or carbon-rich fluid can be accomplished by fluid inclusion studies. Fluid inclusions studies will also constrain entrapment pressure and temperature, and sample from various levels in the section will yield information on these intrinsic parameters at different stages of evolution of the crust. Sampling the reaction zone at the dike-gabbro transition is also an unparalleled advantage of coring a 3-km hole. This section will allow us to investigate the exchange of elements between the deep crust and the overlying sediment package, tracing the effects of fluid migration through the section. The results generated from coring a deep hole will be contrasted with ongoing studies of intrusive samples from slow ridges (e.g., SWIR, Atlantic), intermediate ridges (Hole 504B), and other EPR plutonic suites (Hess Deep, Mathematician Ridge, Garret Transform). Only by coring a complete, continuous section, however, can these objectives be realized without ambiguity as to the stratigraphic location and history of the samples.

4) PHYSICAL PROPERTIES OF FAST-SPREAD OCEAN CRUST

Structural studies will allow us to directly evaluate the stress regime and gradients in stress, the changes in porosity and permeability, and to measure gradients in these properties with depth through the ocean crust. Paleomagnetic studies will develop the relative contribution of the major lithologic units to the magnetic anomaly amplitude, and a complete logging suite and packer experiments will complement structural, geochemical, and physical properties analyses of the core, as well as providing means to orient the core. These results can be compared with similar studies in gabbroic sections sampled by the successful offset-drilling strategy employed at the Southwest Indian Ridge (Site 735), Hess Deep (Site 894) and the Mid-Atlantic Ridge, south of the Kane Fracture Zone (MARK, Sites 921-924).

5) MOHO OBJECTIVE: NATURE OF MOHO, TRANSITION ZONE, AND THE UNDERLYING MANTLE

Fossil ocean crust preserved on-land in ophiolite complexes characteristically exhibit an abrupt physical transition from centimeters to several tens of meters from gabbroic rocks crystallized from magmas in the crust, to an underlying section of monotonous depleted peridotites - sometimes with an interval of dunite consisting of nearly pure olivine of mantle composition, corresponding to the residues of the generation of magmas. The sharp physical contrast in density between these materials has resulted in this boundary being widely equated with the seismic MOHO in the oceans. The relatively uniform depth of the MOHO, then, has been used, in turn, to suggest that crustal thickness, particularly at fast-spreading ridges, is relatively uniform across the ocean basins. This is the linchpin on which estimates of the volume of past and present basaltic volcanism in the oceans, and therefore the transfer of heat and mass from the interior of the earth to its crust, oceans and atmosphere is based. The direct equation of the seismic MOHO to the crust mantle boundary, however, has been increasingly questioned, and it is now widely believed that at least at slow-spreading ridges, this boundary may correspond to an alteration front in the mantle separating unaltered from partially serpentinized peridotite (e.g. Cannat, 1996). Moreover, reconstructions of the crustal section in most ophiolites have given estimates of crustal thickness generally much less than the 6 to 7-km depth of the MOHO found in the oceans (Coleman and Irwin, 1974). This means that either most ophiolites do not represent typical section of ocean crust, or that the MOHO generally does not represent the crust-mantle transition in the oceans. It is, thus, imperative to test this widely used assumption in a representative section of Pacific crust, where it is generally accepted as an article of faith, by drilling as deep into the underlying mantle section as conditions permit. There are several reasons for doing this, among which is ascertaining that the total crustal section has actually been drilled and that the lithologic crust-mantle boundary truly coincides with the seismic boundary. It is quite possible that the crustal section may contain screens or isolated blocks of mantle rock, thus, it is imperative that drilling in the mantle be deep enough that we are assured that the actual crust mantle transition has been reached.

Once this has been done, we will have the first direct determination of the actual thickness of *in situ* ocean crust, and can assess its bulk composition and internal structure without inference. This can then be used to determine if the composition of the erupted basalts can be used in any way to infer crustal thickness without drilling independent of remote sensing techniques.

A significant question which bears directly on global geochemical cycles is the water budget in the crust. Most models of what goes down subduction zones, and hence is recycled into the mantle, assumes that the mantle section in the down going slab is essentially dry. It is quite possible, however, that the cracking front controlling hydrothermal circulation extends off-axis into the mantle section, and that this zone may actually contain substantial fluids contained in partially serpentinized peridotite. This is important, as while shallow crust and sediments are largely believed to be dewatered during the subduction process, this is not the case for the lower crust and mantle sections, which therefore provide the most important reservoir for carrying water into the mantle. This is a key issue both for crustal recycling, and for understanding the nature of arc and back-arc volcanism. Given the complex process by which ophiolites are emplaced, which is generally accompanied by several cycles of alteration and serpentinization of the mantle section, the only unambiguous way of assessing the water budget in the lower crust and mantle in the oceans is to drill an intact continuous section through the ocean crust and well into the mantle.

The pattern of mantle flow and melt transport beneath ocean ridges is widely debated and believed to be significantly different for fast and slow-spreading ridge environments. Given the close link between melting and mantle flow, the predicted composition of the mantle peridotites emplaced at the base of the crust is highly model dependent. Assessing the composition of the underlying mantle and how it varies with depth beneath the crust is therefore a primary constraint on these models. Given the variability and ambiguous provenance of ophiolites, determination of the *in situ* compositional gradient for fast-spreading ridges requires this to be done *in situ.*

Preliminary studies of partial sections of Pacific mantle peridotite drilled at Hess Deep during Leg 147, showed that these rocks preserved many features related to shallow mantle melt transport (Allan and Dick, 1996; Arai and Matsukage, 1996; Dick and Natland, 1996; Kennedy et al., 1996). The means and manner of melt transport through the shallow mantle to the crust determines much of the stratigraphy of the crustal section and how the chemistry of the lavas evolves. A deep section into the underlying mantle, contiguous with the overlying crustal section, beneath fast-spread crust will also allow us to assess the processes of melt transport through the shallow mantle, how they vary with depth and how they influence melt evolution.

DRILLING STRATEGY

To achieve these scientific objectives, we propose to follow two different paths in parallel:

The first is a long term project with the goal of obtaining a complete section of oceanic crust and shallow mantle. We have known for more than 40 years that fast-spread crust appears both simple and uniform, certainly so in terms of seismic structure (e.g., Raitt, 1963; Menard, 1964). Successful deep-drilling of such crust at any single location is, thus, likely to provide fundamental information which can be extrapolated to a significant fraction of the Earth's surface. However, we know that this project will take years and will require the use of ship with deep-drilling capabilities which can operate in 3500 to 4000-m of water. This cannot be achieved before well into Phase IV of the Ocean Drilling Program. In order to pave the way for a really deep hole, however, we can utilize the existing platform to drill well into seismic layer 3. This will directly address many of the principle questions raised in this report, and will provide badly needed information on how drilling conditions change with depth in *in situ* ocean crust.

Second, in the immediate future we propose pursuing the offset drilling strategy that was initiated at Hess Deep during ODP Leg 147 during ODP Phase III. This will test the supposed lateral uniformity of the lower ocean crust formed at fast-spreading ocean ridges, by drilling multiple holes in critical intervals in tectonically exposed partial sections of the lower ocean crust and mantle. Addressing the issue of the lateral variability of the lower ocean crust is a key issue that needs to be resolved in order to plan and site holes for total penetration in Phase IV.

1) - DRILLING TO MOHO

We propose a three stage strategy for drilling a hole that will eventually penetrate Moho:
1 - select the ideal site and start a hole as soon as the *JOIDES Resolution* enters the Pacific (1999-2000 ?). This can be done during an exploratory leg that should be scheduled as soon as possible.
2 In the event deep-drilling is indeed possible, a more thorough site survey including heat flow, pore water sampling, seismic refraction, and multichannel reflection work should be done. The objectives would be to characterize the site in terms of hydrothermal circulation patterns (up- and down-going limbs, convective versus conductive heat flow, etc) and basement structure (thickness of layer 2, depth to Moho, presence or absence of crustal reflectors, velocity-depth profiles, etc). Then, allocate two or three legs during ODP Phase III to deepen the hole as far as possible (2 to 3-km) with the existing drilling technology to deepen the hole to three kilometers by the year 2003.
3 - Deepen the hole to penetrate the MOHO when new deep-drilling capabilities become available in Phase IV.

What do we know from previous drilling?

Previous attempts to drill crust generated at the EPR have been impaired by difficult drilling conditions. Several dozen holes have touched into basement, but only a very few have penetrated more than 20 m. DSDP Leg 54, which was the last serious attempt to drill this type of crust made many of these attempts. The drilling was west of the EPR between the Siqueiros Fracture Zone and the 9°N non-transform offset in crust no older than late Miocene. The leg was a litany of stuck drill string, rapidly destroyed core bits, short penetration, and abysmal recovery. Only a few scraps of fractured basalt were recovered at most of the sites. A prior attempt to drill fast-spread crust on the Nazca Plate during Leg 34 was even less successful. Several holes were also drilled in South Pacific in crust out to Eocene age during DSDP Leg 92. One of these holes fairly successfully penetrated massive flows (as indeed happened at three sites during Leg 54), but drilling in typical thin sheet flows and pillows was never successful on any of these legs.

The only indications that we can drill basalts of fast- spread crust have been in the western Pacific, in crust of Mesozoic age. Two sites, 580 and 595, drilled during two DSDP legs devoted to installation of down hole seismometers, actually recovered enough rock through several tens of meters to suggest why drilling in younger crust has been so difficult. Besides having a closely-spaced joint structure from quenching, the basalts - sheet flows and pillows - are criss- crossed by dense and complex fracture networks lined with low temperature iron oxyhydroxides, clays, and carbonates obviously deposited by hydrothermal fluids near the ridge axis. The veins occur in crossing arrays reflecting several fracturing events. There is evidence for high rates of fluid flux in the form of vein mineral erosion and redeposition in a widened porosity structure. Because the rocks are old and sediment covered, they have later had more pervasive non-oxidative alteration to green clays. This late-stage alteration largely sealed the original porosity structure of the rocks, more firmly cementing the early fractures, and allowing them to be drilled.

None of these holes in older crust were planned to be deeper than they are. Although previous attempts to drill young Pacific crust have been frustrating, these were carried out more than 10 years ago. Drilling technology has improved, ODP drilling engineers now have more experience in basaltic drilling, and the community is developing a better understanding of the relationship between detailed (fault-block scale) basement morphology and drilling success. In addition, Hole 809C, in Jurassic crust in about 6-

km of water in the far western Pacific, has penetrated as much as 100-m into basement. There is a proposal, currently fairly highly ranked, to deepen this hole and to drill another just east of the Bonin arc, both to depths into basement of at least 300-m. But the water depths there, and at the other locations just described, are too great for these places to be considered for eventual deep-drilling. Based on current projections for the riser system being planned for OD21, we need to determine if similarly cemented rocks can be found in crust shallower than 4.5-km. This restricts our theater of operations to the eastern Pacific, and our search pattern for an eventual deep hole, to crust no older than perhaps Oligocene in age.

Possible Moho Targets

Given these experiences, it is obvious that a hole planned to eventually reach Moho should be initiated in relatively old crust, to avoid the drilling problems of young, fractured basalts. In our deliberations on where to do an exploratory drilling leg, we examined two corridors of the eastern Pacific which offer some initial advantages.

The first of these is a cluster of targets in the north Pacific, situated between Mexico and Hawaii. One of these targets is the original experimental MOHOLE site, which was drilled from CUSS I in 1961 (Riedel et al., 1961). The second target is the Hawaii- 2 Observatory (H_2O) site about midway between San Diego and Hawaii near an abandoned cable which is now planned to be used as a relay for a deep-sea seismic observatory. The drilling target here would have to be within about 1-km of a junction box soon to be installed on this cable. There are two other targets in this general region which were originally surveyed for part of a Pacific drilling transect in 1976. These are survey areas PT-5 and PT-6, which are placed along a nominal “mantle” flow line from the sites drilled in the Siqueiros region during Leg 54.

The second corridor we considered is a strip of super-fast crust east of the East Pacific Rise on the Nazca Plate at about 14°S. This was recently surveyed during the German EXCO cruise. Swath mapping, gravity, magnetics, and heat flow data were obtained. A target on crust of about 8-Ma appears to have achieved a conductive temperature gradient, suggesting that the crust here may be hydrologically sealed,, thus, amenable to drilling.

The next two sections discuss these northern and southern corridors separately, outlining what is known about each. Additional acquisition and examination of survey data are required before deciding which of these, or perhaps some other place, is best suited for a leg of preliminary drilling. The two sections are followed by a third section justifying the next phase of drilling beyond exploration, that is for a hole 3-km deep into fast-spread crust. Our report concludes with a synopsis of what may be accomplished by additional offset- section drilling at Hess Deep.

A - The Northern Corridor

There are several targets for potential deep-drilling of fast-spread ocean crust west of San Diego. These include one of the original targets for the MOHOLE Project, the Experimental MOHOLE site, which was drilled from the barge CUSS-1 in 1961. Another possibility is the H_2O (Hawaii-2 Observatory) site, which has already been proposed as a place for a permanently instrumented seafloor observatory, because a communications cable already runs through it. A third possibility is an old deep-tow survey area between these other two, which was cited as a model hole for the recent International Workshop on Riser Drilling in Japan (Larson, 1997).

The Experimental MOHOLE site, drilled near Guadalupe Island (Mexico) in 1961 (28.9°N, 117.5°W) , has 182-m of sediment overlying basalt, about 4 m of which was cored. Water depths is 3566 m. The oldest sediments are Miocene in age. The location was the subject of an excellent seismic refraction experiment (Raitt,1963), which since then has been carefully processed (Spudich and Orcutt, 1980). Seismically, this target is highly representative of fast-spread crust. The sedimentary section was recently piston-cored at a nearby location during Leg 166. Some basalt was also cored. Complications with the site are its occurrence near some fairly large seamounts, and that because of plate reorganizations since the Miocene, the spreading rate here is intermediate rather than fast. Temperatures at Moho depths are likely fairly high, about 300 degrees centigrade (Larson, 1997).

The Deep Tow site (32.3°N; 125.7°W)is in 4200-4280 m of water, with 40-60 m of sediment cover on crust dated from magnetic anomalies at 30 Ma. This date is also prior to the Miocene plate reorganization that affected the Experimental MOHOLE site. The site has several advantages: 1) the existing deep-tow survey (Luyendyk, 1970) establishes that it has normal abyssal hill topography, and provides some locations for sedimented spud in; 2) the water depth is near that being proposed for the eventual riser length for OD21; 3) the crustal age is sufficient that it will have experienced most of the alteration that we wish to understand with deep-drilling; 4) the crustal age is also sufficient that temperatures at the bottom of a MOHOLE at this location will be manageable (just >200°C; Larson, 1997).

The Hawaii-2 Observatory (H_2O) site (Fig. 1) meets many of the requirements of the ocean lithosphere community for drilling in fast-spread crust. The site lies along a long, straight spreading segment between the Molokai and Murray Fracture Zones between magnetic anomalies 18 and 22 (38.5 to 48.9-Ma). The crust accreted between the Pacific and Farallon plates under “normal” spreading conditions at a “very fast” half-rate of 7-cm/yr. Water depths in the area (140°W to 143°W) are 4,250 to 5,000-m. Since the region lies outside the relatively high productivity waters associated with the California Current, sediments here may be thin, perhaps only a few tens of meters, though it may be considerably thicker where it is locally ponded between abyssal hill fault scarps. Exploratory drilling at the site requires a brief site survey, which is scheduled for 1997, using swath mapping and single channel reflection profiling to determine if there is sufficient sediment thickness (at least 100-m) along the cable to install a traditional re-entry cone and to identify the orientation and scale of the short wavelength seafloor features. After the exploratory phase of drilling, this would also likely produce at least be a shallow borehole for long term geophysical and geochemical experiments.

There is overlap with ION and OSN objectives for a permanent seismic station at the site. There is also the potential for continuous, real time monitoring of borehole instrumentation, which could be used for active-process studies. This is a powerful incentive for drilling at the site. The Hawaii-2 cable is a retired ATT submarine cable between California and Hawaii. There is a funded NSF program to cut this cable about half-way and to install a junction box into which a broad spectrum of seafloor instrumentation could be connected. The H_2O observatory also plays a role in three major new seafloor initiatives: the Ocean Seismic Network (OSN; Purdy, 1995), the International Ocean Network (ION; Montagner, 1995), and Borehole Observatories, Laboratories and Experiments (BOREHOLE; Carson, 1996). A letter of Intent to drill at the H_2O site has been submitted to the JOIDES office. It includes the seismic scientific justification for drilling, a discussion of the H_2O observatory program, site selection requirements and large-scale maps of the available geophysical data. The precise location of the H_2O observatory is not critical to the seismic program but the PI’s would prefer that it be located near 140°W.

On balance, a target something like the Deep-Tow site may provide the best combination of factors - water depth, crustal age, Moho temperature, simplicity of tectonic environment - for the 21st Century MOHOLE. All of these sites, however, have the logistical advantage of being only a few days steam from San Diego or Hawaii.

B - The Southern Corridor

One end-member for ocean crust formation is represented by the “superfast” spreading East Pacific Rise south of the Garrett transform fault boundary. Here the ridge crest is uncharacteristically devoid of any transform faults for nearly 1150-km. The axial zone has a blocky crestal ridge and, in contrast with the undulating axial depth exhibited by the northern EPR axis, the southern axis south of the Garrett transform has a nearly constant depth of 2650-m. Crustal accretion is also very uniform along axis and the thickness of the extruded basalts rapidly increases by a factor of two within 1 to 2-km of the ridge axis and remains nearly constant afterwards.

The idea that simple crust is created on super-fast-spreading ridges is supported by the geophysical survey conducted during the German EXCO cruise in late 1995. The exercise explored 720-km long tectonic corridor (0-8 Ma old seafloor) which intersects with the EPR between 14°S and a minor ridge axis discontinuity at 14°27’S. Seafloor roughness derived from swath-bathymetry (Atlas Hydrosweep) is generally 40 to 60-m. Some areas display an increase in roughness and several larger seamounts are superposed on the crust, but the rms height of abyssal hills is generally less than 100-m. This style is still typical for fast-spreading crust and is supported by six airgun/OBH refraction lines. These measurements reflect a relatively homogeneous crustal structure with a well defined 400 to 800-m thick layer 2A, a about 1.2-km thick layer 2B and a lower crust (layer 3) with a much smaller velocity gradient than the layer 2. Velocities are between 6.7 to 7.2-km/s. These measurements show that the igneous section of oceanic crust averages 6.2-km, which is typical for fast-spreading crust.

Compressional wave velocities from layer 2A suggests that velocities increase rapidly by about 40% close to the ridge axis (within 0.5-1 Myr). Afterwards, velocities increase slowly to a value of mature oceanic crust (4.3-km/s) within 8 Myr (Grevemeyer and Weigel, 1997). This two-stage evolution of the seismic properties of layer 2A (fast at young ages, slowly thereafter) is believed caused by the ridge crest and ridge flank hydrothermal circulation system. Changes in physical properties are believed to be caused by sea water-rock interactions, which are controlled by the amount of sea water seen by the rock (the water-rock ratio), and by the temperature of reaction. In general, the higher the temperature, the faster and greater the extent of reaction. This implies that the high-temperature axial system, with its rapidly moving hydrothermal fluids, is accompanied by a comparatively large amount of hydrothermal alteration and sealing of open void spaces. In the ridge flank system, the chemical reactivity is reduced at the much lower temperatures. Because the rate of crustal crack filling depends on the availability of alteration minerals and on the vigor of hydrothermal circulation, plugging of pore spaces and changes in the seismic velocity structure occur slowly away from the ridge crest and cease in a closed system.

The values of a mature layer 2A for 8 Myr old oceanic crust suggest that crustal evolution is at its end. This is supported by regional heat flow measurements (Weigel et al., 1996). The scatter of individual values decreases between 5 to 8 Myr and the heat flux approaches the trend of the plate cooling model at about 8 Ma. One advantage of this location for drilling is that “superfast” spreading crust is believed to consist largely of flow units which should be easier to drill than thin sheet flows encountered during previous attempts to drill basement in the Pacific.

The EXCO-cruise (Weigel et al., 1996) collected swath-bathymetry, refraction and single channel seismics, Parasound echography (3.5 kHz), heat flow measurements and magnetics. In 1998/99 a two leg cruise of the R/V Sonne, including additional geophysical measurements and sampling of rocks and sediments, has been proposed.

C - Backup site: 504B

If the exploratory drilling leg turns out to be unsuccessful, we propose returning to Site 504 as a back-up site. There would be no attempt to re-occupy Hole 504B, which is generally believed to be in too poor condition for further drilling, but instead, a new hole, close by, would be drilled and cased without coring to a depth close to that of Hole 504B. From this point, the Resolution would then resume coring deeper into seismic layer 3, until a depth of at least 3-km was reached. Although the spreading rate here is intermediate, there was a consensus with the scientists in the other working groups that drilling into gabbroic layer 3 should be done here if it was not done on fast-spread crust, in order to meet the minimum scientific requirements of the broader lithosphere community for ODP Phase III.

Technological requirements

Our experience at Hole 504B indicates that drilling 2-km into basement is feasible. It is noteworthy here that this hole was never designed to be drilled deep and was never properly cased. The principle cause of failure of the hole is likely its condition, with many breakouts making it nearly impossible to fully flush drill cuttings out of the hole. As a consequence the drill string frequently jammed whenever rotation and pumping is stopped to retrieve a core. Thus, it is reasonable to assume that with a properly cased hole designed for deep-drilling, we can do much better, and current technology should be sufficient to reach the 3000-m intermediate depth goal during Phase III of the Ocean Drilling Program (1998-2003). However, using the existing technology includes deploying a nested casing system and operating up to the 7.5-km limit of the present drill string with which there is presently little experience.

2) OFFSET DRILLING AT HESS DEEP

As opposed to slow-spreading ridges, the East Pacific Rise is quite flat, and even formation of the faults which bound abyssal hills rarely exposes more than 100-m of rock, all of it basaltic lava. We cannot easily get at rocks of the dike sequence, gabbros, and peridotites, and certainly not in an active axial setting. Significant vertical offsets of the East Pacific occur at major transform faults, of course, but these are quite widely spaced, and only the very largest (and regrettably most remote) present plutonic rocks to the dredge or submersible explorer. How typical these exceptional exposures are of sub-axial assemblages elsewhere along the EPR is also conjectural.

There is one place where lower crustal and upper mantle rock assemblages of the East Pacific Rise have been exposed by faulting which potentially may allow many of the questions we have about crustal accretion, axial metamorphism, and hydrothermal circulation to be answered. This is Hess Deep, which occurs in deeply foundered crust of the East Pacific Rise at the western tip of the Galapagos (or Cocos-Nazca) spreading center in the eastern equatorial Pacific (Fig. 2). This is not a fracture zone. Instead it is a type of rift valley resulting from the divergence in spreading directions of the Cocos and Nazca plates away from the Galapagos micro plate and triple junction. Along the flanks of Hess Deep, there are near vertical marginal rift faults, including exposures along uplifted horst blocks, offering cross-sections through lava pillows and sheet flows, sheeted dikes, and uppermost gabbros. The floor of Hess Deep includes a substantial tilted block - an intra-rift ridge, consisting mainly of gabbros and serpentinized peridotites. The deep-seated rocks have been sampled at various places by dredging, submersible, and drilling, the latter during ODP Leg 147 (Gillis, Mével, Allan et al., 1994). Although there may be structures elsewhere along the East Pacific Rise, particularly at other micro plate triple junctions, with exposures similar to those of Hess Deep, at present Hess Deep is the best surveyed and sampled among them. It therefore offers the best opportunities for continuing studies of lower-crustal rock assemblages, hence crustal architecture, along the East Pacific Rise.

Hess Deep has a drawback: the age of the rocks exposed there is quite young. They are within about 70-100 kilometers of the East Pacific Rise,, thus, are no more than about 1-1.5 Ma. They may have been exposed by rift faulting quite soon after their freezing and crystallization at the Rise axis., thus, they do not carry a significant history of post- emplacement off-axis hydrothermal circulation and alteration. Indeed, along the intra-rift ridge, much of their fairly extensive alteration must be attributed to reaction with sea water introduced in the course of transcurrent faulting associated with propagation of the Cocos-Nazca spreading center to the west relative to the eastward spreading of the Cocos and Nazca plates.

The Hess Deep outcrops mainly offer an opportunity to understand processes which occurred at and near the zone of crustal accretion during the first 500,000 years of spreading. Many of the hydrothermal and structural processes, then must be sorted out from the extensive metamorphic overprint occasioned by their exposure at the tip of the Cocos-Nazca Rift. Both the complexity of the outcrops and the extent of that overprint also almost certainly preclude establishing the original character of seismic transitions in the crust., thus, the important and extensive history of alteration and metamorphism of fast-spread crust - that associated with the majority of lithospheric cooling and subsidence - and the nature of the crustal seismic structure, can only be fully explored by off- axis drilling in significantly older crust.

This means in simple terms that if we want to know what intact fast-spread ocean crust is like, structurally, seismically, hydrologically, and geochemically, we still have to drill it elsewhere, starting at the top, proceeding through lavas and dikes, and then into gabbros and the upper mantle.

Objectives

The tectonically exposed outcrops at Hess Deep have been previously dredged and sampled by submersible (Francheteau et al., 1990; Hekinian et al., 1993), and include extensive exposures of diabase dikes, gabbros, dunites, and partially serpentinized residual mantle peridotites. Although the original basement stratigraphy has been extensively disrupted due to faulting and slumping, it is clear that substantial kilometer scale intact blocks are present and that a crude lower crust and upper mantle stratigraphy is preserved exposed on the northern wall of Hess Deep along the south facing slope of the Intra-rift high. Hekinian (1993) study the dive and dredge samples in detail and makes a respectable case that they represent a stratigraphy similar to that exposed in the Oman Ophiolite, with a thick lower crustal section preceding downwards from sheeted dikes, to isotropic gabbros, through more primitive layered gabbros, then dunites, and finally residual mantle peridotite at the base. The entire sequence is then modeled as a thick crystal mush zone overlying the mantle which contains increasingly evolved gabbros higher in the sequence, broadly consistent with present models for fast spread lower ocean crust based on geophysical constraints such as the detection of the melt lens and position of the present day MOHO. The case is made, however, on the basis of matching individual dive and dredge samples to lithologies in the Oman sequence, and making the argument that the entire Oman section is represented at Hess Deep. This is supported by a somewhat tenuous stratigraphy based on the relative positions of different lithologies sampled up the slopes of the intra-rift high.

The inherent problem here is that this argument is similar to that made in the Atlantic for the presence of large magma chambers. There several different investigators noted that dredged gabbros showed the same chemical fractionation trends as large layered intrusions, believed to represent fossil magma chambers on-land. Again, individual dredge and dive samples could be matched to petrographically similar samples in the layered sequences. However, once a thick sequence of abyssal gabbros was drilled in the rift mountains of the slow-spreading SW Indian Ridge at Hole 735B, it was seen that the physical stratigraphy was totally unlike that of a layered intrusion, and instead represented numerous small cross-cutting intrusive bodies, with a complex syn-tectonic history involving late stage focusing of melt by shear zones. A stratigraphy representing the opposite extreme of a large layered intrusion.

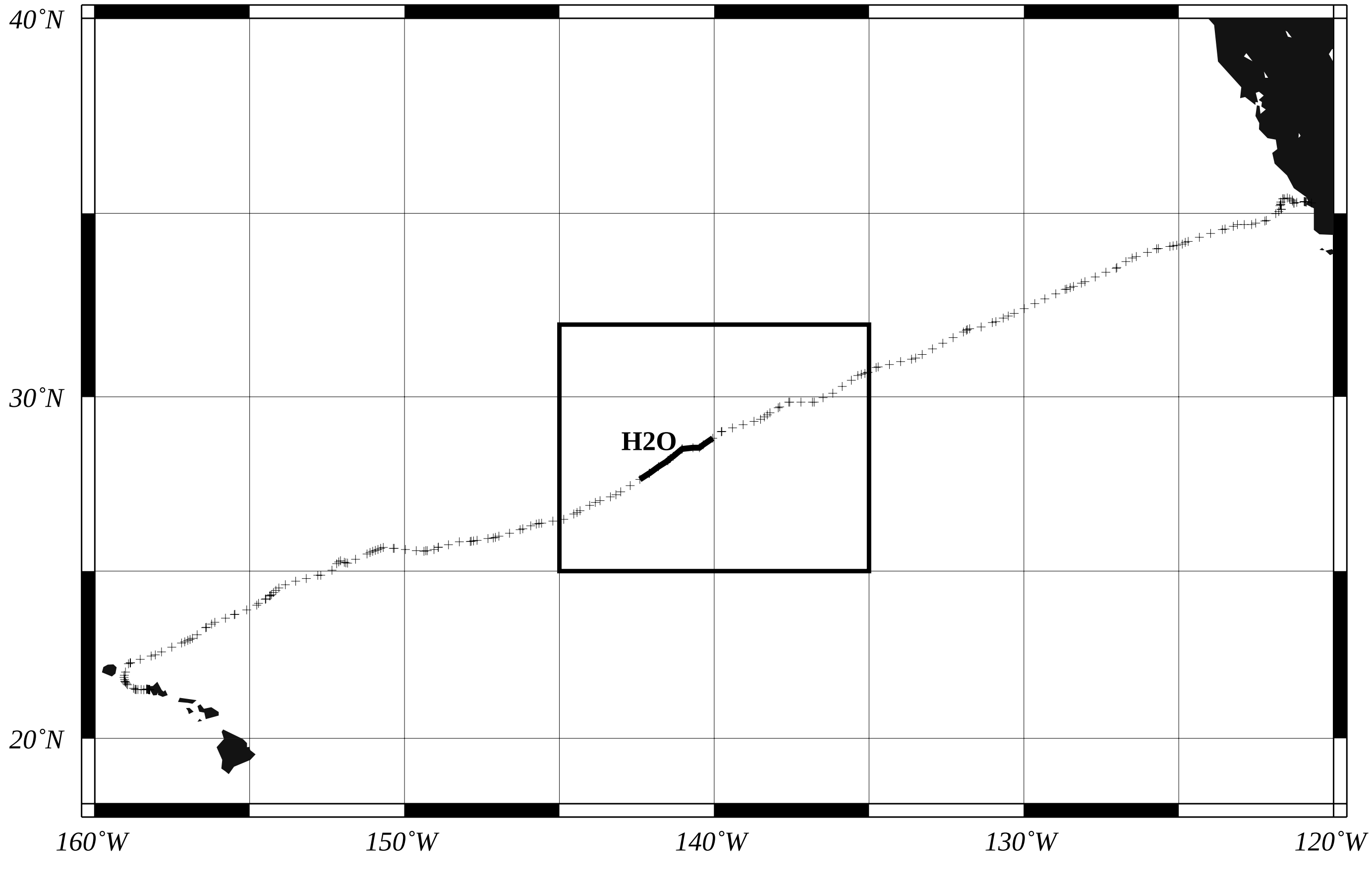
Drilling, however, can make the case that the Hess Deep gabbros represent a thick intrusive sequence similar to that exposed in Oman as suggested by Hekinian, with a systematic progression in chemistry and texture from base to top representing progressive crystallization of gabbros upward through a crystal mush zone to a melt lens immediately beneath the gabbros. ODP Leg 147 drilled a 154-m section of gabbros believed to have been emplaced immediately beneath the sheeted dikes at Hole 894G and a sequence of dunites and gabbros cross-cutting depleted mantle peridotites at Site 895. The former are consistent with what is expected as the capping sequence in the gabbro section crystallized immediately beneath the sheeted dikes at the Oman Ophiolite, while the latter is consistent with gabbros and dunites cross-cutting the mantle section at the base of the Oman Ophiolite. Each sequence has the limited chemical and textural variability expected for sampling different stratigraphic intervals of an Oman-like sequence, and is quite different than what was drilled at Hole 735B, effectively bracketing most of the chemical variability of the entire Hess Deep gabbro suite (Fig. 3). The objective of further drilling then would be to locate and drill a series of 100 to 200-m holes situated in portions of the wall of the Intra-rift high representing different potential levels in the lower crustal sequence. If the gabbros do represent an Oman-like sequence, then each of these holes should again have a more limited petrographic and geochemical variability than the sequence as a hole, consistent with different levels in the Oman stratigraphy.

At the present time a site survey is required to locate outcrops and identify their characteristic lithologies across the intra-rift high in order to plan a systematic offset drilling leg. Although the outcrops have been tectonically disrupted, careful survey can identify outcrops close to major lithologic boundaries such as the base of the sheeted dikes or near the crust mantle boundary. Spacing several holes along these boundaries would then allow evaluation of the lateral heterogeneity of the deep crust and shallow mantle at the two major interfaces for melt transport (dike/gabbro and crust/mantle). Drilling a suite of holes up and down the exposed gabbro section would at the same time permit reconstruction of the composite section, and its comparison to the Oman-type sequence and that drilled previously at the slow-spreading SW Indian Ridge (Hole 735B).

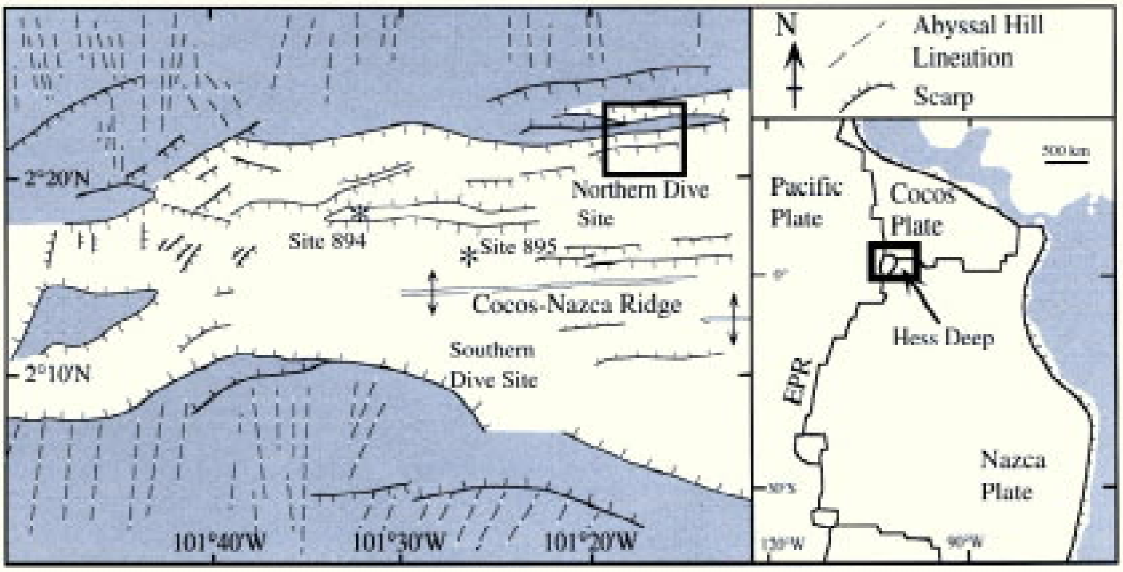
Technological Requirements and Alternate Strategies

Leg 147 proved to be technically difficult, because of: 1) steep slopes partially covered with thin talus; 2) the fractured nature of the basement along the intra-rift high, likely due to the opening of the deep. These two factors made this area strikingly more difficult to drill than the undisrupted section found at Site 735 in the Indian Ocean (Gillis, Mével and Allan, et al., 1994). To overcome these problems, ODP in now developing a hammer-drill-in-casing system that should be tested in 1999. Although, the principle objectives of the offset drilling can be accomplished with 50 - 150 m single bit holes (as successfully drilled on Leg 147), longer sections would be substantially more useful in characterizing the sequence., thus, if the hammer-drill-in-casing system proves effective, we would expect to deploy this tool to drill shallow re-entry sites along the intra-rift high (200 to 300-m). In addition, we would further modify the basic plan outlined above by attempting to deploy the hammer-drill-in-casing system where the dike-gabbro transition is exposed on the steep northern wall in an undisrupted section on the steep northern wall of Hess Deep (Francheteau et al., 1990). If this is successful, then we would pursue the alternate strategy of drilling as deep as possible in this hole, on the assumption that drilling conditions in the undisrupted section would be much better than those on the tectonically disrupted intra-rift high.

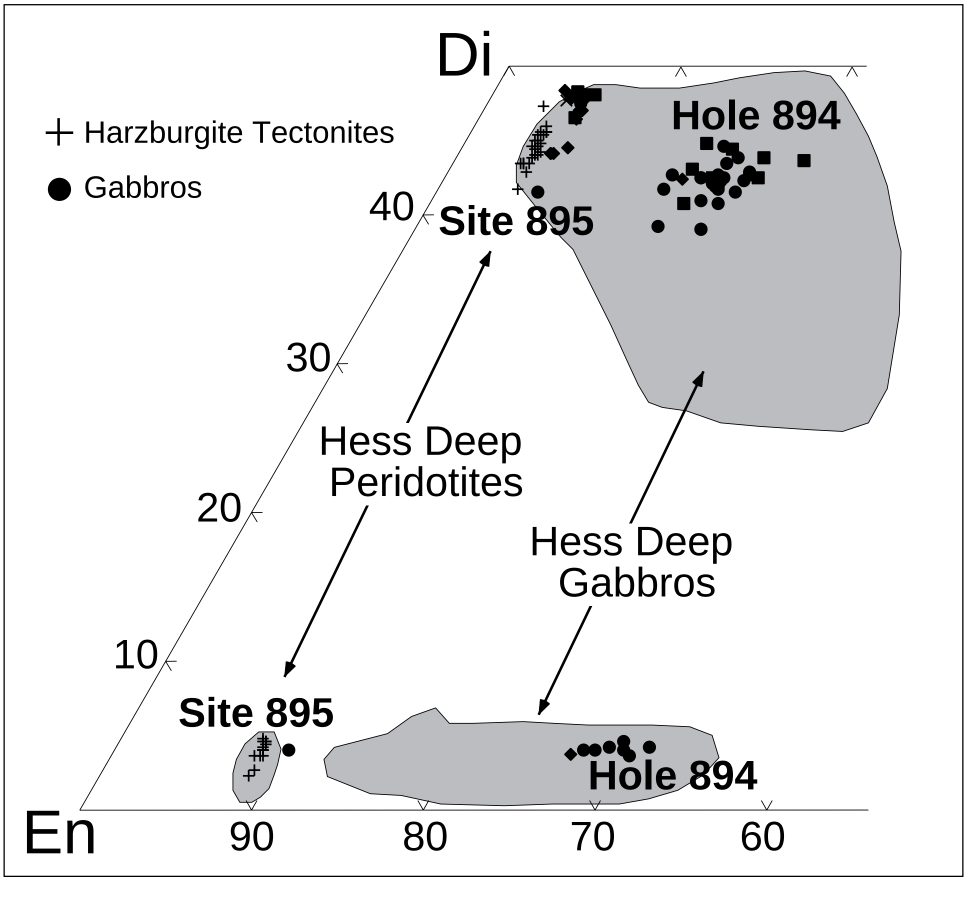
Hawaii-2 Cable and Observatory Locations



Section 4.1, Figure 1: The locations of the repeater boxes for the Hawaii-2 cable (+) are shown. The H_2O observatory should be located between 140°W and 143°W (bold line on cable track).



Section 4.1, Figure 2: Schematic tectonic map of the western tip of the Cocos-Nazca rift showing the locations of Site 894 and the North Slope dive site, from Natland and Dick (1996) as modified from Gillis (unpubl. data). The inset on the right shows the location of the major plate boundaries based on Lonsdale (1988) and Francheteau et al. (1992).



Section 4.1, Figure 3: Pyroxene quadrilateral modified from Dick and Natland (1996) showing the composition fields of pyroxenes in Hess deep gabbros and peridotites from Hekinian et al. Plotted for comparison are the composition of pyroxenes in peridotites, dunites and gabbroic dikes from the shallow mantle section drilled at Site 895, and the composition of pyroxenes in the high-level isotropic gabbronorites and olivine gabbros drilled in Hole 895. The first section represents the magma conduit system in the shallow mantle feeding the overlying gabbro sequence, and the pyroxenes have the most magnesian (En-rich) compositions of any Hess Deep gabbros. In contrast, the gabbros from Hole 894 appear to represent a section close to the base of the sheeted dikes, but likely below the magma lens (Natland and Dick, 1996). The limited range of pyroxene compositions from these two horizons is consistent with a thick chemically downward graded sequence similar to that found at the Oman Ophiolite (Hekinian et al., 1993).

4.2 - SLOW-SPREADING OCEAN RIDGES WORKING GROUP REPORT
Lithospheric Architecture at Slow-spreading Ridges

Participants: R.C. Searle (chair), S. Allerton, M. Cannat, J. Casey, R.S. Detrick, L. Dmitriev, G. Früh-Green, G. Hirth, P. Kelemen, J. Lin, R. Rihm, L. Silantyev, B. Tucholke.

Key recommendations

We propose two drilling experiments on the Mid-Atlantic Ridge to determine (A) the structure and composition of the crustal component of slow-spreading oceanic lithosphere and its evolution in time, and (B) the along-axis chemical and structural variations in the uppermost mantle and its relation to the slow-spreading crust. We recommend that an ODP Working Group for *Crustal Drilling of the Mid-Atlantic Ridge* be set up as soon as possible to develop detailed drilling plans and address site selection and survey requirements.

Experiment A will require an initial phase of drilling an array of six single-bit holes in 2-10 Ma crust, three along the trace of a segment center and three along the gravity anomaly high near its end.

In a second phase, two holes will be drilled to the maximum depth obtainable by *JOIDES Resolution* to contrast the segment center and the segment end.

In the final phase, these last two sites would be extended or redrilled using new technology to achieve total crustal penetration.

Experiment B will require seven single-bit holes drilled into serpentinized peridotite in near-zero-age seafloor, using the *JOIDES Resolution*. These holes will address the nature of the uppermost mantle, and asthenospheric flow and melt migration mechanisms at a slow-spreading ridge.

In a second phase, a site would be selected near one of these holes to achieve deep crustal penetration and determine the lithology of the geophysically defined crust.

An unexplained, first order observation is that igneous crust has variable thickness and is locally absent along slow-spreading ridges, but apparently has nearly constant thickness at fast-spreading ridges. The proposed drilling experiments will directly address the reasons for this difference, focusing effort on crustal variation along a “normal” segment of the northern Mid-Atlantic Ridge and on an “end-member” area to the south, where igneous crust is virtually absent on the scale of hundreds of kilometers along axis. These holes will finally allow us to study complete crustal sections at a slow-spreading ridge. They will allow us to determine the lithology of the geophysically defined crust, and will show the degree to which the lower crust varies along segment and with age. The proposed drilling will reveal the geochemistry and melt emplacement mechanisms of the whole system from the mantle, through the lower crust and magma chamber(s) to extrusives, and will address the nature of asthenospheric flow and melt migration mechanisms in the uppermost mantle.

Scientific rationale

Our aim is to understand the nature and formation of the oceanic crust and upper mantle created at slow-spreading ridges and to contrast it with that created at fast-spreading ridges. Over the past 10-15 years, geoscientists have come to recognize that slow-spread oceanic lithosphere differs significantly from fast-spread lithosphere in its degree of segmentation and igneous crustal thickness (see, e.g., reports of the InterRidge Mesoscale Working Group Symposium and Workshop, Durham, UK, September 1993; InterRidge Workshop on 4-D Architecture of the Oceanic Lithosphere, Boston, USA, September 1994; FARA/InterRidge Conference on the Mid-Atlantic Ridge, Reykjavik, Iceland, June 1996 (InterRidge, 1996)). Slow-spreading ridges are characterized by a segmented morphology, and strong along-axis variations of spreading axis depth, seafloor morphology, gravity anomalies, outcropping lithologies, and lava composition. All of these variations are comparatively subdued at fast-spreading ridges.

Individual segments are typically tens of kilometers in length and offset by distances ranging from kilometers to hundreds of kilometers. Offsets less than about 25-km are typically non-transform in nature, and characterized by overlapping, en echelon, or oblique features whose off-axis traces are reflected in oblique, often disconnected, basins and valleys. Larger offsets take place via linear transform faults parallel to the spreading direction. Although transform faults and their fossil fracture zone traces are a major component of classical plate boundaries, the vast majority of slow-spreading segments are bounded by non-transform offsets.

CRUST

Geophysical studies (seismic refraction, and gravity profiling) and seafloor sampling indicate that crust formed at segment centers is thicker (~6 to 7-km) than at segment ends (~3 to 5-km) (Figure 1), and there is a possibility that much of the variation is confined to the lower crust (i.e. seismic layer 3). This crustal thickness variation is believed to reflect both emplacement of a greater thickness of melt at segment centers and the effects of differential tectonic thinning along segments. The variable emplacement is thought to be linked to focused melt migration and/or focused mantle upwelling beneath centers (Whitehead et al., 1984). Either process could cause along-axis variations in lithospheric temperature, with a warmer lithosphere and therefore shallower brittle-ductile transition under segment centers. The young crust is rapidly extended by faulting, which appears to be symmetric across-axis and relatively minor at segment centers, but becomes highly asymmetric across-axis and of great importance at segment ends. It leads to an extreme asymmetric morphology at segment ends, in which the inside corner is unusually shallow and is referred to as an inside-corner-high.

Thus we have a model of a segment in which the magmatic crust is thicker and the lithosphere thinner at the center, and in which both crust and lithosphere are symmetric at the center and asymmetric at the ends. These variations are reflected in the Residual Mantle Bouguer Anomaly (RMBA - the gravity anomaly corrected for water depth and lithospheric cooling, assuming constant crustal thickness), which is typically highly negative (interpreted as thick crust) at segment centers and their off-axis traces, moderately positive (moderately thin crust) along crust formed at outside corners, and highly positive (very thin crust) along the traces of inside corner highs. The thinnest crust occurs under the flanks of the non-transform-offset valleys adjacent to the inside corner highs, rather than under the valley axes.

MANTLE

Detailed sampling, along the length of the SW Indian Ridge and along the Mid-Atlantic Ridge south of the Kane Fracture Zone (24°N), has led to the recognition that ultramafic rocks crop out extensively on the seafloor at slow-spreading ridges. This is particularly so at segment ends where the geophysically-defined crust is thin (3 to 5-km), but also in some places where it is thicker. This has called into question the simple association of the "geophysical" crust with mafic rocks. An alternative hypothesis is that part of the low-density, low-seismic-velocity crust inferred from geophysics is a mixture of mafic and ultramafic rocks exhibiting varying degrees of metamorphism and serpentinization (Figure 2). Drilling has already demonstrated that the layer 2/3 boundary does not correspond to the dike/gabbro transition. The possibility that the Moho is not a simple lithological boundary between mafic and ultramafic rocks, but rather a metamorphic transition within the ultramafic sequence, is a first order question which urgently needs to be addressed. The only conclusive way of determining the correspondence between the geophysical structure and lithology is by deep-drilling. Beyond this, determination of the physical properties of representative rock samples must be used to develop geophysical techniques capable of distinguishing igneous rocks from partially serpentinized, ultramafic "crust", in order for the scientific community to continue to use regional geophysical surveys to characterize global magmatic fluxes at the mid-ocean ridges.

Seafloor spreading requires the upflow of the asthenosphere with associated melting and production of crust and lithosphere, yet our understanding of these processes is largely model-driven, and has not been tested by robust observation. Theoretical models for asthenospheric flow and melt migration mechanisms can be constrained by drilling where there are extensive exposures of peridotite on the seafloor, and a variety of predications can be tested.

Geodynamic processes can also be addressed in a unique way by mantle drilling. To understand the overall structure of the ridge axis it is necessary to understand the nature and evolution of strain partitioning involved in bringing ultramafic rocks from the asthenosphere into the lithospheric mantle, as indicated by the evolution of tectonic fabrics and fault rocks. Furthermore, mantle drilling can be used to determine the paleo-geotherm beneath a slow-spreading ridge. The crystallization temperatures and pressures of gabbroic intrusions within peridotite record the pressure-temperature path of the ascending mantle within the lithosphere. Spinel crystals within residual peridotites can be used to characterize the cooling rate of the lithospheric mantle, and together with the spreading rate this information may even be used to constrain the physical upwelling trajectory.

Our knowledge of the oceanic mantle is largely based on observations from dredge samples, which are highly altered, and yield little information on the spatial variability or on the scales of mantle heterogeneity. Drilling is the only way to detect the presence of volumetrically minor veins which may play a major role in melt transport, and is the only way to evaluate the relative proportions of different residual peridotite lithologies. Contact relationships between different lithologies can only be recovered by drilling, and provide essential data in understanding melting and melt extraction processes.

Planning for ridge drilling

Over the past few years the mid-ocean ridge community has recognized the understanding of the "four-dimensional architecture" of slow-spread lithosphere as one of its key outstanding scientific problems (InterRidge Mesoscale Working Group Symposium and Workshop, Durham, UK, September 1993). Both InterRidge and RIDGE have convened international meetings (4-D Architecture of the Oceanic Lithosphere, Boston, September 1994 (InterRidge, 1995); RISES meeting, Boston, September 1994: Lin et al, 1994) to begin the detailed planning of integrated interdisciplinary experiments to tackle this problem, and have recognized Ocean Drilling as a vital component of these.

The 1994 InterRidge meeting in Boston developed an outline for a scientific plan for the study of ridge segmentation which is summarized in Figure 3. It envisages a strong framework of geophysical and geological work around two segments, complemented by flow-line and isochron arrays of sampling and drilling, and culminating in drilling two deep holes for total crustal penetration, one centered on an RMBA high and the other on an RMBA low. Geophysical work would include regional gravity, bathymetry and magnetics, regional and segment scale seismic experiments, and near-bottom high resolution mapping and imaging. An important objective of the higher resolution work would be to link outcrop geology to the broader and deeper structure. This plan included an array of drill holes along an outcropping belt of serpentinite to address along-segment variations in mantle chemistry and structure.

Our working group took this plan as a starting point, and refined the drilling component of it. However, whereas the InterRidge plan envisioned that the array of serpentinite holes would be in the same segment as the other studies, we have compelling reasons for believing that many of the crustal and mantle objectives can best be addressed in two separate areas. Below, we develop plans for two geographically separate, though thematically linked, experiments to achieve this.

The MAR between about 22° N and 35° N has an extremely well developed segmentation pattern and includes a number of areas that have been intensively studied, but does not have extensive outcrops of mantle peridotites. In this area, we are confident that a suitable site exists for our crustal objectives (Experiment A), though we have not yet selected a specific site. Recent work has identified a region, centered on the Fifteen-Twenty Fracture Zone at 15°20' N (also known as the Cape Verde Fracture Zone) and extending for more than 200-km along the Mid-Atlantic Ridge, where peridotite forms more than half the outcrop area, and sparse lava flows are locally emplaced directly on a peridotite seafloor without intervening gabbro. This represents a situation of nearly "amagmatic" spreading which is unknown in the Pacific but which may be typical in the equatorial Atlantic as well as at "super slow" spreading ridges. In addition, there is a strong gradient in basaltic lava composition as a function of latitude along the ridge. The region thus offers unparalleled opportunities for studying melt generation, mantle deformation patterns, and the effects of variable mantle composition and temperature on ridge morphology and lava chemistry. It is ideally suited to drilling to understand melt formation and extraction processes, but its off-axis segmentation pattern is poorly developed compared with other areas so that it is not ideal for understanding crustal thickness and other within-segment variables. We therefore choose this area for the mantle drilling objectives (Experiment B).

The following sections of this report therefore deal separately with these two components of our plan.

Experiment A: Crustal drilling

(Contributors: Allerton, Cannat, Detrick, Hirth, Lin, Rhim, Searle, Tucholke)

SCIENTIFIC RATIONALE

The aim of this experiment is to characterize the crustal structure in the center and at the end of a single well-defined slow-spreading segment, and its variation with time.

One of the most important questions currently facing the mid-ocean ridge community is the origin of so-called Mantle Bouguer Anomaly "Bull's Eyes", i.e. the MBA lows that occur over segment centers. Do these indeed reflect variations in crustal thickness and, if so, what is the nature and cause of the variations? Do the MBA lows in segment centers, which we interpret as evidence for thick crust, actually correspond with areas of thick igneous crust? At segment ends, where the MBA is high, indicating thinner crust, can we confirm a smaller thickness of igneous crust? If so, are these variations the result of locally variable mantle melting, or has melt been focused at segment centers, perhaps by along-axis transport in crustal dikes or by sub-crustal transport? Alternatively, are along-axis variations in crustal thickness the result of inhomogeneous stretching and thinning? Interpretations of seismic refraction suggest that along-segment variations in crustal thickness occur mainly in seismic layer 3 (gabbroic rocks according to the ophiolite model), but this needs to be confirmed, and at present there is no suggested mechanism to explain it.

Off-axis geophysical studies to crust of ~10 Ma or more show that the segmentation pattern evolves over time. Segments may lengthen or shorten along-axis, and migrate up and down the axis. Gravity measurements suggest that, even at the center of a single segment, the crustal thickness may vary significantly with time. Such variations are suspected to result mainly from variations in the magmatic flux to the segment, but may also be related to variations in tectonism. A full understanding of ridge segmentation requires this hypothesis to be tested.

Another vital aspect of the time-evolution of the crust concerns its alteration and metamorphosis. Lavas erupted onto the seafloor are fresh and generally have high porosity. As the crust evolves, accumulation of sediment and hydrothermal deposits in their interstices, and consolidation due to burial, will reduce their porosity and permeability and increase their density and seismic velocity. The depth of hydrothermal circulation in the crust is not well constrained, but it has a vital effect on crustal temperature, and hence rheology and deformation. Hydrothermal circulation will also evolve with time, first being open to the seafloor, and later probably occurring in closed systems capped by sediment. The change from one regime to another will have important effects on the alteration of the crust, but its timing is currently not well constrained.

Variations in the gravity signature between lithosphere at the inside- and outside-corners of both transform and non-transform offsets has been interpreted as indicating extensive crustal thinning by faulting in the inside-corner. Both geophysical and geological observations indicate relatively symmetric faulting at segment centers, but highly asymmetric faulting at segment ends. Lower crustal and upper mantle rocks are exposed on inside-corners by what some have suggested are low-angle detachment faults, analogous to those which have exposed metamorphic core complexes in subaerial environments. The characterization of tectonic processes along the length of segments and over the full depth range at which they operate is vital to understanding the development of segmentation and the early evolution of the oceanic lithosphere. We need to know how extension is accommodated in 3D, and how it is partitioned into brittle, ductile and magmatic processes. Critical to this characterization is determining the rheology and strain localization in the mid- and lower crust.

Geochemical studies indicate that at least some extrusives are derived from lithospheric magma chambers, and plutonic rocks have been extensively sampled by dredging. However, we know nothing of the size, position, average composition or longevity of magma chambers, which have never been imaged geophysically on the Mid-Atlantic Ridge, except where it is under the influence of the Icelandic hot spot along the Reykjannes Ridge (Sinha et al., 1997 ; Constable et al., in press). We do not know how melt is delivered to the crust from the mantle, or how melt moves from magma chambers to the seafloor. Is lateral diking important? Can significant chemical fractionation occur in magma chambers and/or during magma transport? More generally, how closely does the architecture of the oceanic crust follow the ophiolite model? Ophiolites are potentially very powerful analogues for aiding the understanding of ridges. They have traditionally been seen as fitting the layered seismic model of the crust, although recent recognition (at ODP hole 504B) that the seismic layer 2/3 transition does not correspond to the dike/gabbro contact casts doubt on their applicability. Moreover, geochemistry suggests that many ophiolites are from arc or back-arc environments. By determining how well (or poorly) the crust of the Mid-Atlantic Ridge follows the ophiolite model, we shall be in a much better position to use knowledge of ophiolites in interpreting ridge structure and processes.

Virtually all of the questions discussed above require drilling to answer them, and many of them require drilling to mid- and lower crustal levels. It must be emphasized that exposures of lower crustal rocks are rare at segment centers. Lower crustal and upper mantle rocks may be exposed at segment ends or be accessible to offset drilling, but only in this very particular tectonic environment; this gives us no information about segment centers. Furthermore, offset drilling does not allow the comparison of upper and lower crustal rocks that formed coevally, although such comparisons are vital for understanding issues of magma differentiation and transport. Equally, comparison of rocks formed along the same isochron but at both segment center and segment end is needed for addressing questions of along-axis melt differentiation and delivery. Drilling is also necessary to recover samples whose spatial relationships are known, whether it be to sample successive lavas in a continuous pile (e.g., to establish their chemical evolution), to examine dikes and veins in relation to their host rocks, or to examine the development and structure of strain localization in faults and ductile zones. Oriented samples will be important for structural and paleomagnetic studies. In addition to samples, drilling enables further characterization of the rock column through logging and down-hole experiments. Examples are the determination of crustal porosity and permeability, their evolution with age, and their relation to hydrothermal alteration and seismic velocity. Emplacement of down-hole seismometers will significantly enhance the ability to image the crust tomographically.

DRILLING STRATEGY

The experimental objectives will be approached through three phases of drilling. Phase 1 is within the present capabilities of the *JOIDES Resolution* and should therefore happen prior to 2003 (Phase III of the Drilling Program). Phase two (1 to 3-km deep holes) is within the nominal capability of the Resolution. Its implementation should therefore start prior to the end of the present ODP program in 2003. It offers a precious opportunity to test the JOIDES potential for deep hard rock drilling. Stage 3 requires deeper drilling capabilities and should be competed during Phase IV of the Drilling Program.

Phase 1

During phase 1, an array of six single-bit holes will be drilled in 2-10 Ma crust along two flow-lines, one in the RMBA low at the segment center, and one on the RMBA high at segment end (Figure 3). Along each flow-line, the holes will be sited on local RMBA extrema to sample temporal variations, with two of the segment center holes on local lows and one on a local high, and two of the segment end holes on local highs and one on a local low. Detailed surveys may show that the local RMBA highs at segment ends expose important structural and stratigraphic relations that reflect exhumation of the deep lithosphere and the accompanying transition from ductile to brittle deformation (i.e., the detachment model). In this case, two or more drill sites may be needed on one of these features in order to sample and correlate these relations within the mapped geological context of the seafloor. Precise site selection should follow extensive dredging and near-bottom surveying and imaging (to determine local variations in geology, lithology and geochemistry). All holes should be logged if possible, and at least some would be instrumented for further studies (e.g. segment scale seismic studies using natural earthquakes).

The single-bit holes will serve the dual objectives of comparing the shallow crust formed coevally at the segment center and the segment end, and of investigating the temporal variability of this crust. However, they will also serve the vital function of testing and selecting sites for the deeper drilling that is to follow, so that we follow a strategy of gradually focusing and deepening as the project extends.

While the segment center holes are likely not to penetrate below the extrusive layer or possibly shallow dikes, carefully sited holes at the segment end should be able to sample lower crust and/or upper mantle. The comparison of segment center and segment end will address the along-axis variability of upper crustal lithostratigraphy (lithologies, volcanic style, magma delivery system), geochemistry (melt composition, source composition, degree of melting, extent of fractionation), and structure (nature of lithological contacts, number and type of faults and fissures, degree and rate of tilting) between segment center and end. It will also address the question of the source of magnetic anomalies in slow-spread crust and of the nature and extent of upper crustal hydrothermal alteration.

Along-flow-line holes will look for similar variations with age. They will assess variations in volume and nature of magmatism and magma source with time, and test whether thick crust correlates with more evolved chemistry, higher degree of melting of the mantle source, or variations in source composition. These holes will also address the question of crustal aging. They will examine the chemical alteration of the crust; the nature, depth, and duration of specific alteration and mineralization events; evolution from open to closed hydrothermal systems; and evolution of crustal porosity profiles.

Phase Two

Two reentry holes will be drilled to the maximum depth achievable with *JOIDES Resolution*, probably in the range 1 to 3-km. Sites for these will be selected along an isochron, based on drilling conditions observed during phase one: one on the RMBA low at segment center, and one on the RMBA high at segment end.

These holes will extend the along-segment comparative studies to the mid crustal levels: determining the thickness of extrusives at both places, and the nature and depth of the seismically defined layer 2/layer 3 boundary. They will allow for detailed studies of magma chambers in slow-spreading environments, linking both the chemistry and the melt delivery systems to the extrusive layer directly above. Important questions on strain partitioning and mid-crustal flow and faulting will also be accessible.

These holes will provide the opportunity to do deep crustal monitoring experiments (e.g., heat flow, seismicity, hydrothermal flow etc.). A further possibility at this stage, though of lower priority, is to drill the conjugate outside-corner crust for comparison with the inside-corner on the opposite plate. This would directly test ideas of highly asymmetric crustal generation and extension. For example, it would give a measure of the total amount of extrusives produced at the axis, and how they are subsequently partitioned into the two plates.

Phase Three

The last stage would involve the drilling, at or near phase two sites, of two deep holes for total crustal penetration, using new technology. The hole at the segment center will need to be 6 to 7-km deep, starting in seafloor 2 to 3-km deep. The segment end hole will be shallower (3 to 4-km), but possibly located in deeper seafloor (up to about 3.5-km). These holes will need to be cored and logged to the maximum extent possible. They will finally make it possible to study complete crustal sections, allowing us to determine the lithology of the geophysically defined crust. They will show the degree to which the lower crust varies along segment, and will reveal the geochemistry and melt emplacement mechanisms of the whole system from mantle, through lower crust/magma chamber to extrusives.

Our working group did not discuss the implementation of this deep-drilling phase in great detail. Drilling to intermediate depths during Stage 2 is expected to take a significant number of legs (4 to 6); thus, Stage 3 is unlikely to begin until well after the end of the present drilling program. The opinion was also expressed that although total crustal penetration was an exciting objective at slow-spreading ridges, it was more of a priority for fast-spreading settings (where crustal structures are expected to be less heterogeneous and where seafloor exposures of ultramafic and gabbroic rocks are uncommon).

SITE SURVEYS AND SELECTION

The drilling sites for this experiment will be part of a multi-disciplinary and multi-scale study of Mid-Atlantic ridge segmentation (as outlined in the InterRidge and Ridge workshops; Figure 2). It is essential that all drilling be done within areas where the full geological context of a drill site is understood from detailed seafloor mapping and sampling. Thus, our preliminary recommendations for survey requirements are as follows: complete bathymetric, gravity and magnetic coverage up to 10 Ma, detailed seismic refraction and tomographic experiments, deep-towed high resolution side scan sonar and magnetic survey, and extensive rock sampling and visual observation using towed vehicle, ROV or submersible.

Experiment B: Drilling a serpentine belt along the Mid-Atlantic Ridge at 15°N

(Contributors: Casey, Cannat, Detrick, Dmitriev, Früh-Green, Hirth, Kelemen, Silantyev)

SCIENTIFIC RATIONALE

The aim of this experiment is to characterize upper mantle and melt geochemistry, melting and melt migration mechanisms, deformation structures in the asthenospheric and lithospheric mantle below the ridge, and hydrothermal alteration, as well as the variation of these characteristics along axis. It involves the drilling of an array of seven single-bit holes in exposures of serpentinized peridotites that form a significant part of the axial valley walls in the 15°N region. In a later phase, a site would be selected near one of these holes to achieve deep penetration into seismically defined crust and determine its lithology.

It has been hypothesized that oceanic crustal thickness is largely independent of spreading rate, and is a function only of mantle temperature. However, along slow-spreading ridges, regions of normal mantle potential temperature have been found to have thin and/or discontinuous magmatic crust. Along the flanks of the Mid-Atlantic Ridge south of the Fifteen-Twenty Fracture Zone, peridotite crops out nearly continuously, and in some cases lava flows lie directly over it, without intervening gabbroic “lower crust”. This occurs both at segment ends and segment centers. This indicates that the ridge here is a “magma-starved” extreme end-member compared to the magmatically “robust” East Pacific Rise. It has been proposed that this results from a combination of slow-spreading rate and limited magma supply, with extensive conductive cooling of the upper mantle restricting the depth interval of decompression melting and initiating the onset of crystal fractionation at substantial depths (ca. 25-km?) beneath the seafloor. Such a process may be common along the Mid-Atlantic Ridge.

Related to this is the petrological hypothesis that Mid-Ocean Ridge Basalt (MORB) at slow-spreading ridges is compositionally distinct from that at fast-spreading ridges, due to the deeper onset of fractional crystallization. This can be directly tested if extensive samples of plutonic rocks emplaced within peridotite can be obtained. As suggested in the introduction, studies of gabbros can be used to determine the paleo-geotherm and even the trajectory. Sampling by dredging and from submersibles has yielded gabbroic dikes within peridotite; however, sections of more extensive “cumulate” gabbro bodies, in which the vector of geochemical variation can be used to provide additional constraints on the pressure of crystallization and the nature of liquids extracted from these bodies, can only be obtained by drilling.

Surprisingly, geophysical surveys of regions of the Mid-Atlantic Ridge that have abundant outcrops of residual ultramafics yield significant crustal thicknesses. This paradox represents a first order problem. If geophysical surveys are to be used to estimate magmatic flux, they must be calibrated to detect the difference between igneous crust and crust composed predominantly of altered mantle peridotite. Obtaining extensive samples of altered mantle-derived peridotite from well below the surface weathering horizon in order to determine their physical properties is a fundamental step in resolving this problem.

Conductive cooling has predictable effects on axial deformation patterns: the upper limit for low-stress asthenospheric flow in the axial upper mantle should be located at depths greater than the base of the crust. Crust in the axial region must be directly underlain by a root of cooler mantle able to sustain significant deviatoric stresses. The existence of this rigid mantle lithosphere has been inferred from thermo-mechanical models of axial valley formation, but such models are built on rheological estimates based only on small-scale, laboratory rock deformation experiments.

Micro-structural studies of ultramafic rocks collected in the walls of the Mid-Atlantic Ridge median valley indicate that 1) there is much strain localization in the ductile part of the mantle lithosphere, and 2) samples of these rocks retain a good micro-structural record of successive deformation events, from the onset of conductive cooling until their emplacement near the seafloor. The first point indicates that the uniform rheology often used for modeling misses essential processes in the deformation of mantle lithosphere beneath slow-spreading ridges. The second offers a way to unravel the deviatoric stress, strain, temperature and deformation history of this lithosphere. These control both the mechanics and geometry of the axial region and the mode of magma emplacement. Is mantle deformation characterized by “three-dimensional” patterns with radial expression in plan view? Does the shallow mantle undergo “corner flow”, developing a sub-horizontal, Moho-parallel foliation? Drilling is the best way to get ultramafic samples that can yield such information, because it provides vertically continuous sections that can be at least partially restored to their ridge-axis orientation. Because the objective is ultimately to constrain the lithosphere rheology at the scale of a few tens of kilometers, samples are needed from several sites distributed along-axis at this length scale.

The temperature and depth of onset of hydrothermal alteration affect both the rheological parameters in the axial lithosphere and the nature of the crust-mantle boundary in regions of extensive ultramafic outcrop. This is because serpentinization produces decreases both in the resistance to brittle failure and in seismic velocity and density. ODP legs 109 and 153 showed that some ultramafic samples have been serpentinized at over 350°C. Such temperatures correspond to depths of several kilometers below seafloor, consistent with Hess’ hypothesis that the Moho could locally be a serpentinization front. In order to test this hypothesis, we need to constrain serpentinization conditions in a significant number of subseafloor ultramafic samples again distributed over along-axis distances of a few tens of kilometers.

In some regions along slow-spreading ridges, major element indices suggest an unusually high degree of mantle melting, if one assumes that the source composition and melting processes are constant. In contrast, trace element indices, interpreted in the same way, would indicate a very small degree of melting; thus the mantle source composition and/or the nature of the melting process is probably not constant along the ridge, as is partially borne out by radiogenic isotope ratios. Classically, such areas are interpreted as mantle “hot spots” (e.g., the Reykjanes Ridge south of Iceland). Because temperature and geochemical enrichment are correlated in a way that is poorly understood, and which may vary from place to place, there is little quantitative understanding of the relative importance of these factors in controlling geodynamically important variables such as crustal thickness, axial depth and geoid height. The contributions of mantle temperature and composition can in principal be sorted out in the Fifteen-Twenty area, which is unusually deep and has thin to absent igneous crust. On this basis, one would predict a cold mantle with very little partial melting during decompression. Paradoxically, the peridotites consistently record high degrees of melting in their major element concentration, while many basalts show characteristics of long-term enrichment. Thus, in this region, geochemical indices of mantle temperature and enrichment contrast strongly with geodynamic indicators of mantle temperature. There is a substantial geochemical gradient over just 150-km along the ridge in the Fifteen-Twenty area, from geochemically “normal” MORB in the north to strongly “enriched” MORB in the south. It is vital to investigate whether there is a geochemical gradient in the peridotites that is parallel to that in the basalts. Surface samples are insufficient: they have an inherent bias toward “resistant” lithologies, and provide an incomplete record of the nature and scale of geochemical variability at each site. Only by drilling can we obtain unbiased recovery of critical but volumetrically minor components in the peridotite.

A final first-order goal in the 15°N region will be further characterization of the known hydrothermalism associated with peridotite and plutonic rocks. Although such activity is unique among known hydrothermal sites, exposures of ultramafic and mafic rocks on the seafloor are fairly common at slow-spreading ridges. Both high and low temperature interaction of such rocks with sea water may therefore be an important part of the global geochemical budget for many elements. For example, reaction with peridotite may be important in controlling the amount of subducted Boron, and methane contents in hydrothermal plumes are known to be significantly higher over regions of ultramafic and gabbroic exposure.

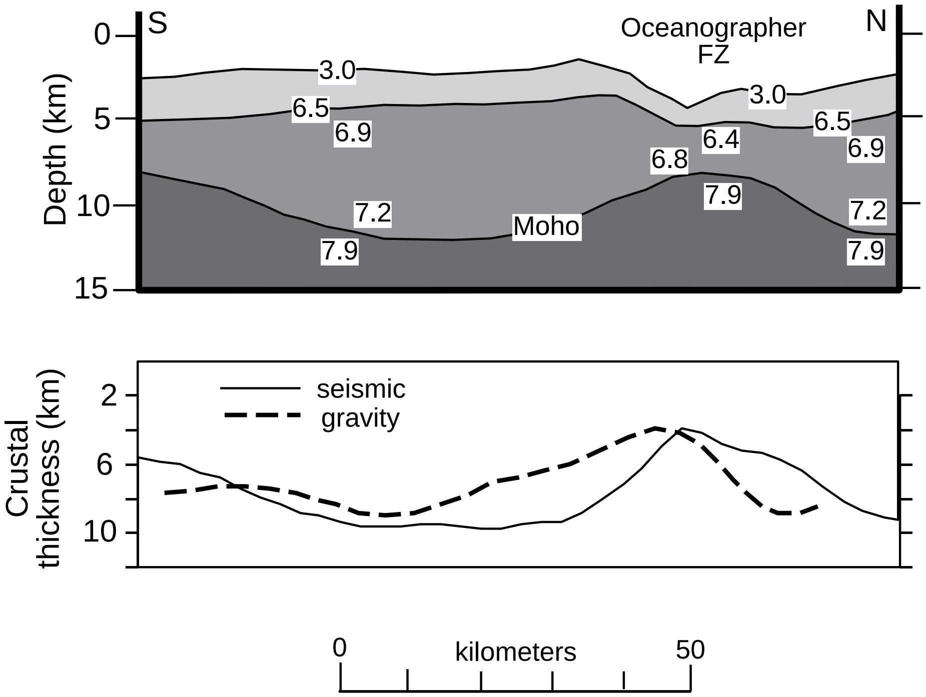
DRILLING STRATEGY

The first phase of drilling in the 15°N region requires one leg of single-bit drilling. One single-bit hole would be located in serpentinized peridotites on one of the walls of the axial valley north of the Fifteen-Twenty Fracture Zone (Figure 4) to serve as a geochemical reference, since basalts in this part of the ridge are N-MORBs. South of the fracture zone, basalts are progressively more enriched in incompatible elements, up to 14°N where the ridge has a shallow bathymetry and a small axial valley suggesting a hot thermal regime and a large magma supply to the crust. Extensive dredging has shown that serpentinized peridotites crop out along both walls of the axial valley between the fracture zone intersection and 14°43’ N, about midway up the basalt geochemical gradient. The six other single-bit holes will be distributed along-axis in this region of geochemical gradient. This is within the present capabilities of the *JOIDES Resolution* and should therefore happen prior to 2003 (Phase III of the Drilling Program).

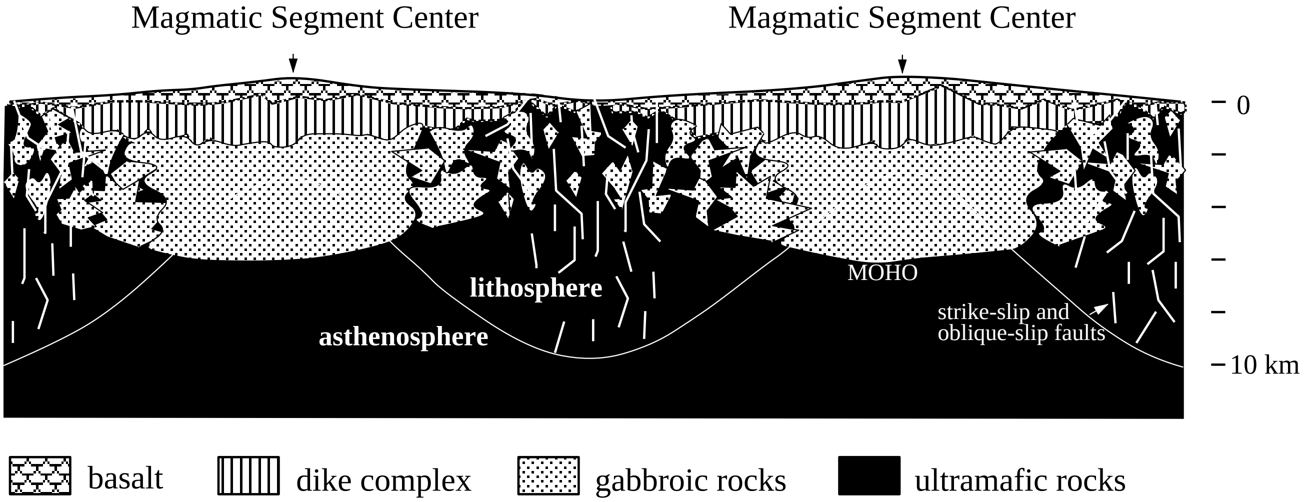
In a later stage of drilling, which has not been discussed in detail by our working group, we would select one of the sites drilled during the first leg to start a deeper, re-entry hole. This later phase would represent a number of legs using either the present nominal capabilities of the *JOIDES Resolution* for deeper re-entry drilling, or the deep-drilling capabilities of a modified or new platform.

SITE SURVEYS AND SELECTION

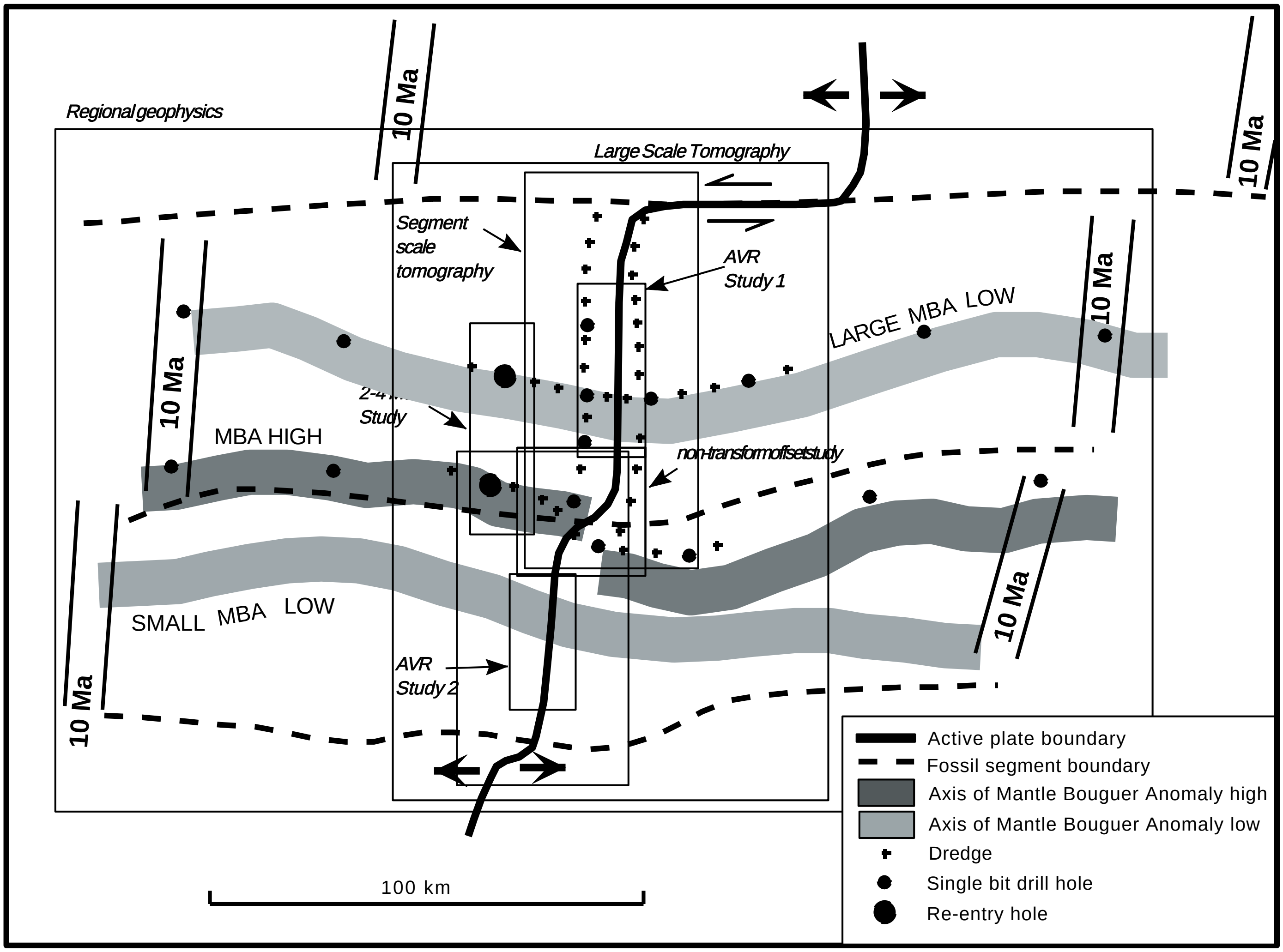
The 15°N region has been extensively studied by dredging and some submersible dives, but does not yet have adequate geophysical characterization (there is a limited bathymetric coverage shown in Figure 4, two along-axis gravity profiles near zero age, and local magnetic data). The following surveys are required: bathymetric, gravity and magnetic survey up to at least 6 Ma (in order to characterize axial segmentation), seismic tomography and/or refraction experiment, deep-towed side scan sonar and micro bathymetric surveys and additional dredging and diving focused on prospective drill sites.



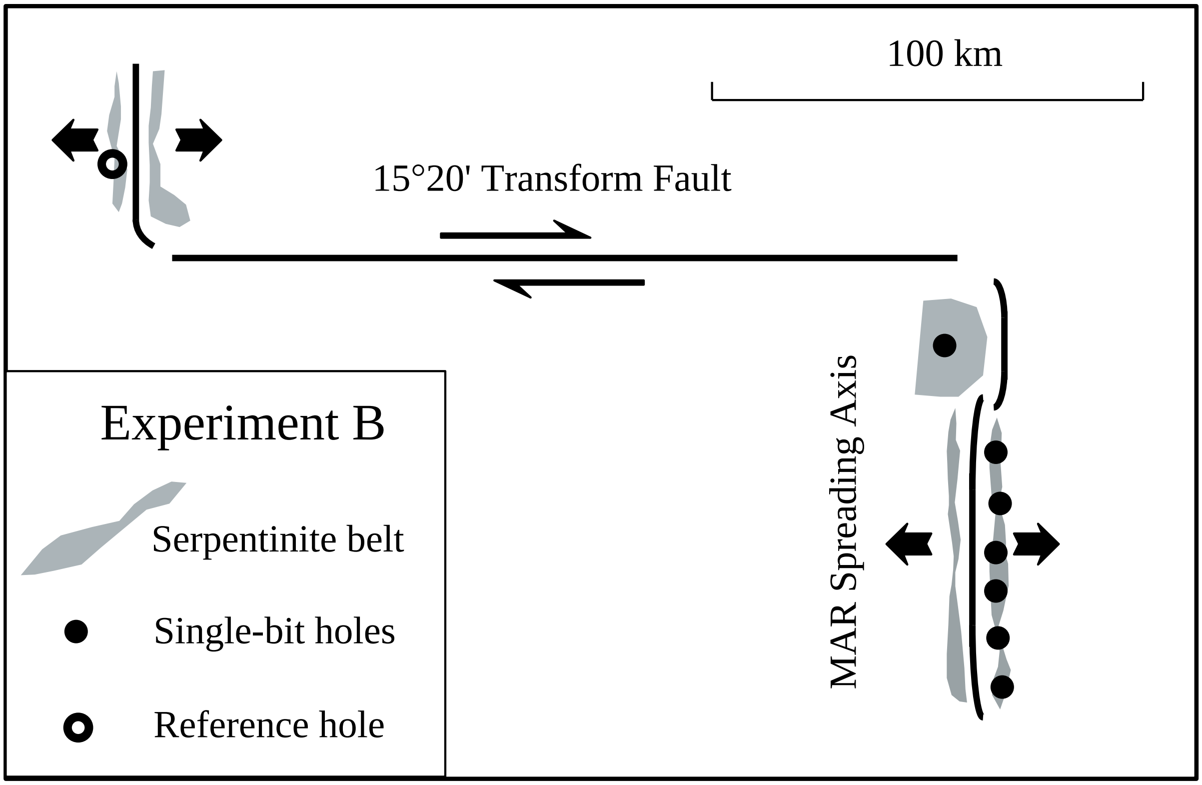
Section 4.2, Figure 1: Seismic crustal structure across the Oceanographer Fracture Zone from Sinha and Louden (1983) as modified by Detrick et al. (1995). Seismic velocities are in kilometers per second.



Section 4.2, Figure 2: Sketch from Cannat et al. (1995) showing along-axis section of two idealized magmatic segments (4X vertical exaggeration). Lithosphere is inferred to be 10 km thick beneath segment ends, on the basis of natural seismicity data. Minimum lithospheric thickness beneath centers of segments is arbitrarily chosen as 2 km. Depth to Moho is shown as 4 km at ends of segments and 7 km at segment centers, on the basis of gravity and seismic data. Magmatic crust is shown as continuous and layered at magma-rich segment centers but thinner and more discontinuous towards magma-poor segment ends where ultramafic outcrops are common.



Section 4.2, Figure 3: Slow-spreading ridge Experiment A modified from the InterRidge Meso-Scale Workshop Report: *4-D Architecture of the Oceanic Lithosphere.*



Section 4.2, Figure 4: Bathymetric map of the 15°20'N region of the MAR outlining possible locations for slow-spreading ridge Experiment B to test the along-axis lateral variability of the shallow mantle.

4.3 - ACTIVE PROCESSES WORKING GROUP REPORT

Participants: Mike Mottl (Chair), Jill Karsten (Steering Committee Rep), Susan Agar, Keir Becker, John Delaney, Gretchen Früh-Green, David Goldberg, Debbie Kelley, Robert Kidd, Victor Kurnosov, Marv Lilley, Andy Magenheim, Jim McClain, Peter Rona, Debra Stakes, Damon Teagle, Jean Whelan, Bob Zierenberg, Boris Zolotarev
plus several more who came and went.

Overview

Oceanic crust is the end product of a complex suite of active tectonic, magmatic, hydrothermal, and biological processes, that occur primarily at divergent plate boundaries (i.e., mid-ocean ridges and back-arc spreading centers). Off-axis and intraplate tectonism, hydrothermalism and volcanism subsequently modify the oceanic plate formed at the spreading centers. The last twenty years of seafloor exploration has immensely increased our knowledge of the first-order features of the oceanic crust, the distribution of these components in space and time, and the fundamental processes which govern their formation and evolution. As our insights into the nature of oceanic crust and the processes attending crustal accretion have matured, the focus of exploration has shifted increasingly toward questions about the temporal variability of these processes over observable (i.e., decadal) time scales and the linkages and feedback mechanisms which exist between them. In addition, the recent recognition that significant microbial populations may reside within the upper oceanic crust has raised an exciting new area of inquiry regarding active processes in the oceanic crust. While studying the products of these various processes integrated in the geologic record has yielded valuable constraints on such scientific problems, only by direct observation and monitoring of active processes can these questions be fully answered. Two-types of approaches have been envisioned: *in situ* monitoring of individual sites in order to document temporal changes in specific active processes, and seafloor “observatories”, consisting of networked instrumentation at several sites, in order to establish interactions between different types of active processes. Conducting real-time investigations of active processes is both imperative for answering the scientific problems of interest and a logical extension of the work which has been conducted in the last several decades of ocean crust research.

Ocean drilling has played a vital role in past explorations of the oceanic crust, by providing a window into the sub-surface portions of oceanic crust. Similarly, ocean drilling and instrumented boreholes will provide an integral component of *in situ* and long-term monitoring strategies to study oceanic crust in a variety of tectonic settings. In this report, we briefly describe: 1) the scientific rationale for seafloor observatories and the role of instrumented boreholes for *in situ* monitoring, 2) a number of specific drilling targets and observatory strategies where active monitoring is essential, 3) criteria for site selection and pre-drilling surveys, and 4) technological and logistical considerations that are necessary for these studies to be implemented. Defining the scientific rationale and generic sites for observatories utilizing instrumented boreholes is relatively straightforward, and indeed, has already received considerable attention and discussion (e.g., RIDGE Observatory Framework document, ION Workshop report, Borehole Report). Implementation of and detailed planning for such experiments, however, is critically dependent on several challenging technological advances, which are also discussed briefly here. Active processes are, by their nature, primarily located in areas of young crustal formation, which has been notoriously difficult to drill; thus, most of the experiments described here are strongly dependent on successful development of technologies for drilling in young volcanic terrains (e.g., DCS). Although several recent ODP programs have developed some of the logging and borehole instrumentation capabilities needed (e.g., CORKs), additional types of chemical and physical sensors, tools for “slim” drill holes, and innovative tools/strategies which utilize closely-spaced boreholes (e.g., cross-hole tomography) and seafloor installations, all need to be developed. It is expected that the insights obtained by *in situ* monitoring strategies will ultimately lead to a later generation of innovative "active experiments", which utilize borehole opportunities.

Active processes occur in a variety of tectonic settings on the seafloor, and the basic concept of using borehole instrumentation to study such processes can be applied to many different sites. Four examples of observatory sites are discussed here - 1) a hydrothermally active ridge axis, 2) an off-axis or ridge flank hydrothermal system, 3) a volcanically and hydrothermally active intraplate volcano, and 4) a convergent margin hydrothermal system. Of these four sites, the ridge axis site is given highest priority as a drilling target in the near-term because it represents the first order end-member of ocean crust accretionary processes and because it is one of the most mature and broadly-supported of the programs of this type. At present, there is significant national and international community support for ridge crest monitoring (e.g., InterRIDGE) and there is already a commitment by U.S. and Canadian scientists to instrument portions of the spreading center in the NE Pacific along the Juan de Fuca Ridge. It is important to emphasize, however, that the other observatory targets discussed here (as well as others not mentioned) are as important scientifically, and are considered a very high priority for an extended drilling program or as alternative targets, should the technological developments required for drilling at the ridge axis prove untenable

Key recommendations of the working group

- Highest priority in the Active Processes Working Group is given to drilling and instrumenting 5 boreholes in conjunction with a ridge axis observatory experiment. The ideal configuration would consist of 4 holes to ~500-m depth and 1 hole to ~2-km depth, distributed in an L-shaped array. All five holes would be logged, CORKed and instrumented in order to determine the physico-chemical state of the crust in the region of an active volcano-hydrothermal system and to monitor fluid and geochemical evolution of the hydrothermal system over decade time scales.
- Obtaining the technological capabilities for drilling and CORKing 5 holes to ~500-m depth is considered a very high priority for Phase III (1998-2003) drilling (approximately 2 legs), but requires successful development of hammer-in casings and DCS capabilities in order to be implemented. A new generation of borehole instrumentation and logging tools designed to measure the physical and chemical properties of the system will also need to be developed (e.g., CORKs for "slim" holes produced by DCS).
- Deepening existing observatory holes to 2-km depths at the ridge crest observatory and initiating new observatories at alternative sites (e.g., ridge flank or different spreading rate environment) are identified as very high priorities for Phase IV (>2003) drilling. These experiments will require a *JOIDES Resolution*-like (i.e., non-riser) drilling capability for Phase IV of the program.
- New borehole technologies and shipboard laboratory capabilities for sampling the sub-surface biogeosphere are needed immediately for mapping and exploring this largely unknown component of oceanic crust development and evolution.
- Many of the drilling, coring, and borehole instrumentation technologies required for implementing a ridge axis borehole observatory are similar to those needed by other programs in the marine community (e.g., OSN/ION). It is essential that technological developments be coordinated between these various groups, in order to proceed most efficiently.

- In order to implement the ridge axis observatory experiment, the Working Group recommends that ODP convene a Borehole Instrumentation Program Planning Group which provides oversight to a Detailed Planning Group on a Ridge Axis Borehole Observatory Experiment. This RABOE DPG must have a liaison to the InterRidge Active Processes Working Group, in order to coordinate with other observatory efforts and site selection.

Monitoring of sctive processes: Scientific rationale

SEAFLOOR OBSERVATORIES

The concept of seafloor observatories for *in situ* and real-time monitoring of active magmatic, tectonic, hydrothermal and biological processes has been extensively discussed in recent years, and has been a high priority component of the U.S. RIDGE and InterRidge programs. Numerous workshop reports have detailed the specific rationale for seafloor observatories, most recently the Final Reports for Workshops Addressing Temporal Variability of Ridge Crest Processes, the Framework and Guidelines for the Juan de Fuca Seafloor Observatory document (Spiess et al., 1996), the ION meeting report, and the Marseilles meeting report. The scientific issues which can be addressed by observatories span a wide range of disciplines and spatial and temporal scales. An example of the broad array of questions which has been used to lay the foundation for an observatory approach, repeated from the ION report, includes:

- How often, and in what pattern and quantity, is magma delivered from the mantle to the crust?
- What are the spatial and temporal characteristics of magma movement into the upper crust and onto the seafloor through rifting, diking and eruptive events?
- In what manner does new crust achieve its rigidity and become an integral part of the adjacent plate?
- What are the primary heat transfer, chemical and biological consequences of diking events?
- What are the components and space/time extent of the subseafloor biosphere?
- What are the nature and origins of spatial/temporal variability in submarine hydrothermal systems? What are the dominant physical processes involved?
- What is the space/time extent of exchange of heat, fluid volume and chemical mass between hydrothermal systems and the overlying ocean?
- How do the nature and longevity of hydrothermal systems influence ecosystem development, faunal succession and biological productivity?
- To what degree does hydrothermal venting influence the physical, chemical and biological character of the overlying water column? What is the relative importance of episodic vs steady state outputs?

While these questions represent important research areas on their own, they reach greater potential for making major progress on the fundamental behavior of active seafloor systems when they are studied simultaneously and together. These questions can be addressed by monitoring several key parameters, such as ground deformation (e.g., elevation, strain), seismicity, seafloor permeability, extent and nature of rock alteration and mineralization, and hydrothermal effluent properties (e.g., temperature, velocity, composition, biological activity, water column particulates), as well as detailed mapping and sampling surveys. The compelling scientific arguments which underpin efforts to establish seafloor observatories have led to successful attempts at prototype experiments on the Juan de Fuca Ridge and Northern East Pacific Rise over the last few years. These efforts have recently culminated in the preparation of the Framework and Guidelines for the Juan de Fuca Ridge Seafloor Observatory document (Spiess et al., 1996), which endorses very specific experiments and instrumental needs for realization of a ridge crest observatory. Ocean drilling is identified as an important component of that effort, although specific borehole experiments are not discussed in great detail. Drilling-related aspects of ridge crest observatories are, thus, considered in more detail below.

The questions and strategies proposed in the Framework document are also readily applied to other seafloor sites which involve coupled volcanic-tectonic-hydrothermal-biological processes, such as off-axis hydrothermal systems, convergent margins, and active intraplate volcanoes (e.g., Loihi). Ultimately, when these questions are investigated in a variety of tectonic settings (e.g., fast vs slow ridge axes, intraplate volcanoes, convergent margins), comparisons between the different settings will help establish the control of key first-order parameters, such as spreading rate, pressure and magmatic composition and volatile content, on the nature and evolution of these processes.

Subseafloor biosphere studies

There is one active process associated with development of oceanic crust which has not received extensive discussion by the community — biological activity. It has recently become evident that certain hard rock, subseafloor portions of oceanic spreading centers harbor a substantial, unexplored microbial infauna supported essentially by mantle-derived volatile fluxes focused though divergent plate boundaries. The evidence for this assertion is that in six out of six submarine diking-eruptive events that have been studied, massive effusions of microbial material (e.g. Huber et al, 1990; Haymon et al, 1993; Holden et al, 1996) have been observed and a significant subset have yielded culturable thermophilic archae, or primitive microbes especially adapted for growth in aqueous fluids at temperatures above 60°C.

The precise cause of these outpourings is not certain. Event-triggered changes in flow regime may have flushed existing biological products from the pores and cracks within the seafloor. It is also possible that fracturing and magmatic intrusion may have generated enhanced nutrient fluxes resulting in event-triggered microbial blooms that simply overflowed the confining space in the enclosing rock. In the recent Gorda Ridge event, thermophiles (optimum growth range—40 to 60°C) were cultured from the massive megaplume released within hours to days of event initiation. The 1993 Coaxial event produced culturable hyperthermophiles in vent fluids issuing at temperatures no higher than 18°C, three times lower than the optimal growth range.

It is clear that microbial life forms thrive in water-saturated pores and cracks within deep, volcanically active portions of our planet. In fact, a most intriguing suggestion is that these organisms may be distributed throughout the hottest, youngest rocks on the planet. It may well be that seafloor hydrothermal vent fields are only the “tip of the iceberg” in terms of the total biomass supported by submarine hydrothermal effluent. By designing innovative strategies to explore linkages between active volcanoes and the life forms they support, we gain essential knowledge about processes on our own planet, while obtaining critical new insights about how to explore for life on other planets.

The marine science community and the Ocean Drilling Program have a unique opportunity to assume a defining role in the early exploration of a potentially powerful planetary scale biogeological paradigm. Essentially, the concept that a significant fraction of this planet’s biomass exists within the brittle portion of the oceanic crust, proximal to zones of active volcanism, has gained strong support from observations of submarine diking eruptive events. But it will require drilling integrated into long-term experiments and time-series observations to "flesh out" the concept and to validate the degree to which it is applicable to volcanic systems in general.

Complementary strategies for examining the extent, distribution, abundance, dynamical behavior and nutritional requirements of subsurface microbia communities in active volcanoes should include:

- **Rapid response to diking-eruptive events** — Comprehensive and immediate response with a full suite of interdisciplinary tools and researchers is essential to obtain complete and systematic characterization of the microbial productivity set in motion by these events.
- **Drilling into zones of potential microbial productivity** — Only drilling will enable us to sample directly microbial communities below the seafloor, to explore the depth, variability and abundance of the deep volcanic biosphere. Optimal approaches might involve drilling hard rock targets selected for effluent testing of well-framed hypotheses that bear on the *volcanic ecology* of this newly discovered subseafloor habitat. Especially intriguing will be perturbation experiments using tracer injection of nutrients or even specific microbial strains into arrays of drill holes designed to allow hole-to-hole communication.
- **Long term instrumentation and time-series sampling of known vent fields** — The spatial variability of near subsurface microbial communities may be reflected in output of high and low temperature venting within now stable hydrothermal systems.

Proposed drilling experiments

Active processes which occur in a variety of tectonic settings can all benefit from *in situ* or long-term monitoring strategies which utilize borehole instrumentation. Here, only four types of experiments are discussed. Highest priority for Phase III drilling is given to the Ridge Axis Borehole Observatory (RABO) Experiment.

THE RIDGE AXIS BOREHOLE OBSERVATORY (RABO) EXPERIMENT

Scientific Objectives:

Drilling-related experiments which mesh with the observatory objectives outlined in several RIDGE and InterRidge documents are primarily focused on two aspects: 1) defining the sub-surface physico-chemical structure of the upper oceanic crust, which will fundamentally control the permeability and chemical evolution of hydrothermal fluids that pass through it, and 2) monitoring the physical and chemical properties of these fluids over time scales of several years. Specifically, drilling and borehole instrumentation can be used to assess the 3-D pattern of: lithostratigraphy and alteration assemblages, porosity and permeability structure and their relationship with fracturing, temperature-pressure fields, pore fluid composition and flow direction (both chemical and biological components), and, with deeper penetrating holes, processes which occur in the "reaction zone", where fluid-rock interactions are most extreme. When combined with other parameters measured by observatory instruments deployed on the seafloor (e.g., micro seismicity, vent fluid composition), relationships between sub-surface properties and features expressed on the seafloor can be constrained, and the consequences of perturbations induced by specific magmatic and tectonic events (e.g., dike intrusion) can be determined.

Experimental Design:

The ideal ridge axis observatory experiment will consist of an array of five CORKed boreholes distributed in an L-shaped array (Figure 1). It is expected that this experiment will take a minimum of 2 legs during Phase III (1998-2003) and 1 leg during Phase IV (>2003) of the Ocean Drilling Program.

Phase III: During Stage 1, three holes will be drilled to ~500-m depth and ~500-m apart. In past attempts to drill young ridge crest environments, it has been extremely difficult to spud the drill into the typically rubbly volcanic terrain of such sites. Implementation of this experiment, thus, assumes successful development of either the DCS or a combination of hammer-in casing/DCS tools (see Technology section below). During the initial drilling, holes will be deepened as far as possible without casing, in order to allow logging. Logging-while-drilling (LWD) strategies do not appear to be compatible with the DCS as presently configured, so that logging will have to be done afterwards. During Stage 2, two additional holes will be drilled to ~500-m depth and between 500-m - 2-km from the first three holes, depending on the ridge configuration. At least one of these five holes will penetrate through an active fault zone, in order to evaluate fluid movement along such structures. All five holes will be logged and CORKed with instrumentation for long-term monitoring of the physical and chemical properties of the borehole.

Phase IV: During Stage 3, at least one of the holes will be un-CORKed, cored to a depth of ~2-km, and re-CORKed. The primary objective of this deep hole will be to evaluate chemical processes occurring in the main reaction zone of the hydrothermal system, and their relationship to shallower portions of the system.

Logistical Considerations:

The significant technological constraints associated with this experiment are considered more thoroughly in a later section. Should a combination of hammer-in casing and DCS tools be required, it will be necessary to have a mid-leg port call to reconfigure the deck for the DCS heave compensation system, since it is apparently incompatible with the set-up for hammer-in casings.

Site Selection Criteria and Pre-Drilling Survey Needs:

Site selection of the appropriate drilling targets for any of these efforts should include well-mapped and well-characterized areas in which other international scientific groups or programs are committed to providing substantial supporting activities. In essence, the true power of the drilling capability here lies not in full crustal penetration but in integrating carefully selected arrays of drill sites into the existing planning efforts of groups like InterRIDGE and ION. Thus, the primary site selection criterion is to couple the ridge axis borehole observatory with other efforts to install a ridge axis seafloor observatory by RIDGE and InterRidge, who have already developed criteria for site selection and pre-observatory survey needs (e.g., see Framework document). In addition to those, it would be extremely beneficial to have constraints on the sub-surface hydrology, so high resolution seismic or active EM experiments to define permeability anisotropy are also highly recommended as pre-drilling surveys. One important issue which must be given considerable thought, however, is the impact of drilling on other planned seafloor observatories. Thus, pre-drilling baseline and syn-drilling monitoring studies of the output and behavior of the hydrothermal vent field, in order to fully understand what perturbations have been introduced by drilling into the system, are also necessary.

The drilling configuration outlined above is idealized for a generic spreading center, and the final placement of holes must take into consideration the ridge axis morphology, that will depend to first order on the spreading rate. Furthermore, the scientific questions which can be best addressed by observatory studies, which will dictate the specific type of borehole instrumentation to be utilized, will also depend enormously on the environment chosen. For example, at faster spreading sites, where axial valleys are narrow and shallow, and the crust is structurally less complex and spatially more uniform, site selection may be primarily influenced by factors such as the ease of drilling. At these ridges, the emphasis will naturally focus on shorter time scale hydrothermal phenomena, and their linkages with active magmatism. In the tectonized, broad and deep axial valleys of slower spreading ridges, careful consideration of the structural complexity of the setting will have to be made when selecting specific drill targets. At slow ridges, scientific questions about the temporal variability and evolution of hydrothermal processes over time scales of ~150 kyr or more are better studied because of the complex suite of vents and assemblages exposed (e.g., TAG) in such regions. Ideally, it is anticipated that ridge crest observatories with a borehole component will be realized at both of the tectonic end members (i.e., slow-spreading and fast-spreading ridges), in order to fully characterize their very different modes of crustal accretion.

THE RIDGE FLANK OBSERVATORY EXPERIMENT

Scientific Objectives:

Hydrothermal circulation continues within the crust for millions to 10’s of millions of years after accretion at the spreading axis. Although the fluid flow is lower temperature and more diffuse than the focused axial systems, the longevity and potential volumetric importance suggest that it may play a more significant role in global geochemical cycles. Understanding of the hydrologic and structural controls on off-axis circulation and its linkage with the axial hydrothermal system is at a nascent stage. One such system has been drilled by ODP in the Middle Valley of the northern Juan de Fuca Ridge (Leg 139 in 1991). The Resolution has returned to Middle Valley and the Escanaba Trough in 1996 and will also drill on the distal flank of the Endeavour segment of the Juan de Fuca Ridge. The results of Leg 139 drilling suggest that the off-axis fluids may in fact be derived from a zone of high heat flow nearer the axis, channeled laterally by zones of high permeability that are likely determined by active faults. *In situ* measurements of permeability (packer experiments) and subsequent time series monitoring of pore fluid pressure (CORK experiments) tracked the perturbation and recovery of the flow regime within a few years after drilling. Active experiments planned for the upcoming return drilling leg will test many of the hypotheses based on data from the initial cruise.

Middle Valley, however, is not merely a sedimented section of normal mid-ocean ridge. Contemporaneous sedimentation and volcanic activity has transformed much (if not all) of layer two into a sheeted sill complex. The sill complex imparts a fundamental horizontal control of the permeability structure of the crust. The active hydrothermal vents are sited over a buried seamount which may have provided an off-axis source of heat and topographic dam for the circulating fluids. Although Middle Valley is an extremely important laboratory for ongoing monitoring and active experiments, it cannot be assumed to represent the same structural or hydrologic regime of an unsedimented piece of mid-ocean ridge.

Developing an experimental site on the flanks of an active (bare-rock) axial system is considered a high priority of the Active Processes Working Group. Such a site could optimally be correlated to a suite of observatory experiments and would be correlateable to an observatory site on the zero age crust of the spreading center. A flank observatory would also contribute to monitoring processes associated with the aging of the oceanic crust. Crucial measurements for a flank observatory are the determination of subsurface porosity and permeability structure using long-term (6-12 months) detailed micro seismic studies, seismic refraction and reflection surveys, active electromagnetic studies and detailed mapping of fault distribution. It is essential that these detailed studies occur prior to the system perturbation inherent in a drilling program. One goal of the preliminary studies would be to locate a major active subsurface fault since they almost certainly play a large role in controlling the fluid flow. Intersection of such a structure at two different depths by drill holes (Figure 2) would permit sampling of microbial communities, mineralization and fluids within permeable zones. Cores from deviated boreholes would provide a complete cross section of an active fault for mineralogical, and micro structural characterization. Subsequent isolation and instrumentation of active faults (strain, stress, temperature, fluid flow rates) would permit long-term monitoring of fluid flow and direct correlation of micro seismic activity, movement along the fault and surficial venting. At least one of the boreholes intersecting the fault should be over 1-km deep, as strain measurements at shallower depths are ambiguous. An adjacent deep drill hole (2 to 2.5-km) extended to the dike-gabbro boundary would provide samples of the horizons most likely to be the reaction zones for the high-temperature hydrothermal circulation. An important question is whether the major faults controlling fluid flow off-axis are the same as the on-axis structures, tapping into strongly altered fluids within a deep high-temperature reaction zone. Finally, the relationship of fault movement and fluid flow can be determined by active experiments within CORKed holes, such as those planned for Middle Valley (BOREHOLE Workshop Report p. 81-83; ION Workshop Report p. 44-45) as well as hole to hole tomographic surveys to assess evolution of porosity structure. Concurrent OBS arrays would capture the seismic signature of the failure/movement within the instrumented boreholes.

Experimental Design:

This generic description of a Rise Flank Observatory could be sited in several places. The optimal site would be adjacent to the Ridge Axis Borehole Observatory described above so that the transition from the axial to the flank hydrological and structural framework could be mapped in detail. An alternative site would be in conjunction with the H_2O site being planned for the eastern Pacific. This alternative site is consistent with a drill hole proposed to study fast-spread crust and would benefit from the suite of instrumentation being planned for this Observatory. The H_2O site would have the additional advantage of a cable connection to land-based laboratories, providing a real-time data link.

INTRAPLATE VOLCANO OBSERVATORY EXPERIMENT

It is well-established from studies on active subaerial volcanoes like Kilauea, that intraplate volcanoes are fundamentally different from mid-ocean ridges. Two key differences are the geometry of the volcanic conduit systems (i.e., caldera and rift zone formation) and the volume of magma supply (significantly more than MOR). These differences primarily stem from the different stress regime (i.e., not an extensional spreading environment) and the mantle source and melting conditions of intraplate environments. Comparison of the behavior of the volcano-tectonic processes in the intraplate environment with those found in the MOR environment will, thus, provide important constraints on the behavior of these structures. Furthermore, hydrothermal activity during the submarine phase of intraplate volcano development may prove to have important differences compared with MOR systems, because of the differences in permeability structure (and its influence on fluid flow), magma composition, and low pressures of eruption as the edifice grows (which may allow two-phase separation of hydrothermal fluids).

Loihi seamount is the youngest volcano in the Hawaiian chain in the submarine stage of development, yet it has all of the key attributes of the more mature Hawaiian volcanoes, such as flank rift zones and a summit crater. The summit region is also known to be hydrothermally active (Pele's Vents) with abundant bacterial mats. The HUGO (Hawaii Undersea Geo-Observatory) experiment to establish a seafloor observatory near the summit of Loihi (~1-km water depth) will include seismometers, tilt meters, bottom pressure sensors, cameras, thermal and chemical sensors to monitor earthquakes, eruptions, tsunamis, and related hydrothermal and biological phenomena. The observatory will be connected to the shore of the island of Hawaii via a fiber optic cable donated by AT&T; this cable will allow both "data-up" and "power-down" transmissions. A prototype tilt meter package has already been installed on Loihi, and the fiber optic cable is currently scheduled to be installed within the year. Drilling and borehole experiments which might dovetail with the HUGO experiment would have many of the same objectives as outlined for the ridge axis setting, but the geometry of the borehole sites would have to be tailored to the different geological setting. ODP drilling has been proposed previously for Loihi, with high ranking, and earlier DSDP drilling on the flanks of Iceland (e.g., Leg 38) has demonstrated the feasibility of drilling in this environment.

CONVERGENT MARGIN OBSERVATORY EXPERIMENT

The same scientific questions and strategies which have been outlined above pertain to active processes in oceanic crust associated with convergent margin settings. Of particular interest are the hydrothermal systems associated with submarine fore-arc and back-arc volcanism. These hydrothermal systems, because of the siliceous and volatile-rich magma compositions and low system pressures which can allow two-phase separation in hydrothermal fluids, are of both scientific and economic interest, because they tend to be enriched in precious and strategic metals (see section 4.5, Convergent Margins). This working group did not discuss in detail a specific experimental design for a borehole-based observatory in this environment, but recognized that many of the strategies outlined above are readily applied to this high priority environment.

Technological Requirements

DRILLING/CORING CAPABILITIES

While there is strong consensus among the community that monitoring active processes with seafloor observatories that include borehole instrumentation is of extremely high scientific priority, discussions of how to implement such observatories very quickly encounter a number of logistical constraints which must be considered. Active processes by their very nature occur primarily in young volcanic terrain, whether at a mid-ocean ridge system or intraplate volcano. Drilling into young, unsedimented and uncemented seafloor has been notoriously difficult for the Ocean Drilling Program and its predecessor DSDP, and has spurred efforts to develop new technologies such as the Diamond Coring System (DCS), in order to achieve greater success in such rubbly environments. Previous attempts to drill in young ridge axis environments (e.g., Leg 142 and TAG) have demonstrated the inability of Rotary Coring Bits (RCB) to penetrate the rubbly volcanic surface of the ridge axis environment. DCS was intended to solve this problem, but has been set-back by difficulties during development. The Working Group agreed that DCS is ESSENTIAL to the implementation of the ridge axis borehole observatory experiment, and strongly endorses its continued and expeditious development.

One important result of this working group's discussions was uniform agreement that the most important objective of observatory-related drilling was to obtain boreholes which could host logging and monitoring instrumentation, with the recovery of drill core from that borehole being of relatively lower priority. It was concluded that the most promising strategy appeared to be the use of hammer-in casings, which would hopefully penetrate the most rubbly zone of the seafloor, followed by subsequent deepening with the DCS. Hammer-in casings will not recover the topmost ~40-m of drill core (and possible can be extended to ~150 m), which was considered an acceptable loss, if it meant that the DCS could be more successfully applied in young seafloor environments. These technologies (hammer-in casings and DCS) are expected to be operational sometime during Phase III, and the Working Group endorses all efforts to expedite this process. In Phase IV of the drilling program, observatory-related drilling will involve applying the strategy to new sites and deepening existing holes to ~2-km depths. Both of these can probably be accomplished with a *JOIDES Resolution* type drilling capability (i.e., riser capabilities not required), and the Working Group strongly endorses maintenance of such a capability during Phase IV.

Two additional concerns were addressed by the group. First, the question was raised as to what extent drilling perturbed the hydrologic system which was to be studied by long-term monitoring? Results from the TAG and Middle Valley experiments indicate that some temporary modifications to the flow regime occur as a result of the drilling process, but that an equilibrium configuration can be reattained after a relatively short (< 1 year?) time frame. This problem can also be mitigated by pre-drilling studies of key parameters in the observatory site to establish baseline conditions and monitoring of these parameters during the drilling process with seafloor instrumentation. The second concern raised involved the intrinsic incompatibility of casing boreholes, which is necessary for deepening holes, and the scientific objectives of an observatory, which include logging and monitoring processes within the borehole. Ideally, minimal casing will be installed during the drilling process. Side-wall coring may also be necessary in areas which are cased, although this technology has met with uneven success in the ODP. Furthermore, new casing strategies, which may allow partitioning of the borehole (so that different depth intervals can be monitored separately), would be valuable technological advances for the purpose of observatories.

BOREHOLE INSTRUMENTATION CAPABILITIES

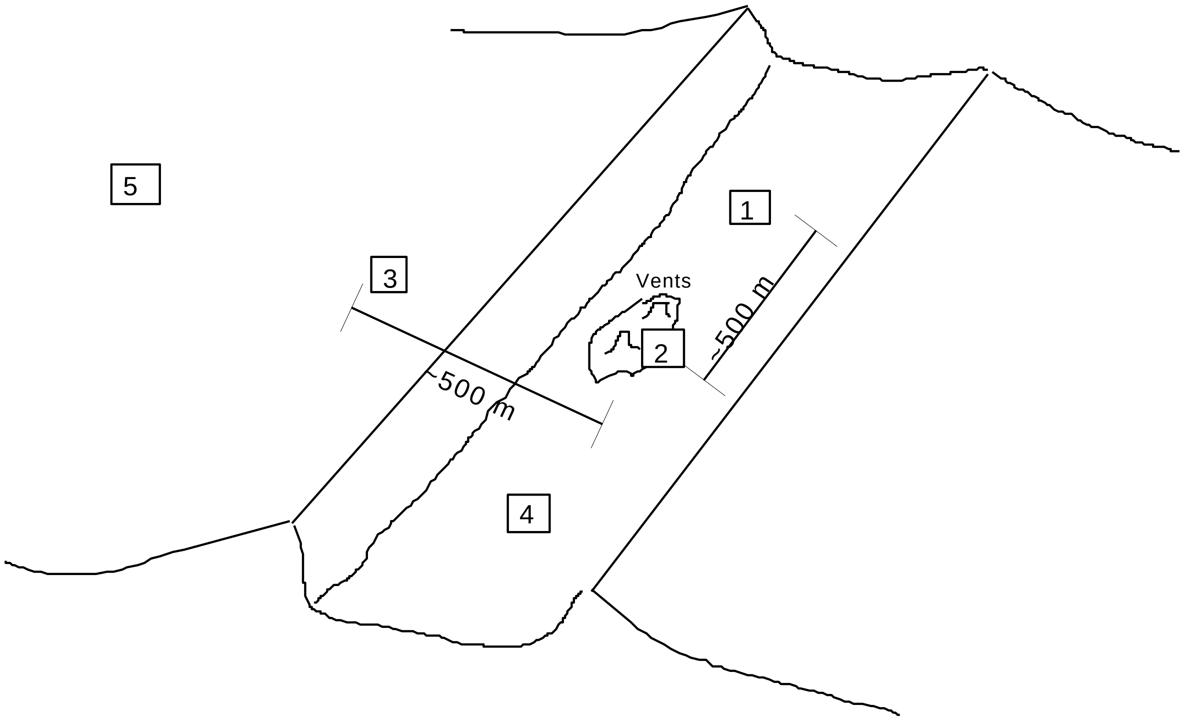
While the benefits of a borehole-mounted observatory strategy are largely self-evident, implementation of such a concept is technologically extremely challenging in terms of down hole instrumentation. Three types of borehole instrumentation will be required for implementation of an observatory strategy: relatively standard down hole logging instruments, long-term borehole monitoring instruments (e.g., CORK), and instruments for cross-hole and "active" experiments. The current status of borehole instrumentation and plans for future development has been clearly summarized in the *Down hole Measurements in the Ocean Drilling Program: A Scientific Legacy* document and the report of the recent workshop on "*BOREHOLE Observatories, Laboratories, and Experiments*" (Carson, et al., 1996). Although several of these tools, or prototypes, already exist, a key issue concerns modification of these tools for the "slim" holes (~4") that would be produced by DCS coring, as well as instrumentation that can withstand possibly high temperatures and corrosive fluids in the ridge axis hydrothermal environment.

Utilization of an instrumented borehole seal (Circulation Obviation Retrofit Kit, CORK), has been highly successful for monitoring pressure and temperature changes within boreholes at several sites over a period of several years. Active experiments (e.g., packer and pump tests) have been successfully carried out at Hole 892B on the Oregon Margin (Screaton et al., 1995). CORK-to-CORK experiments to examine hydrologic communication and permeability structure have been conducted during Leg 169. Prototype fluid samplers, which can be used to monitor geochemical and biological components within the borehole are also under development (e.g., Stakes et al., 1995). Borehole broad band seismometers are currently being developed in conjunction with the Ocean Seismic Network (OSN) program, and a pilot experiment at site 843B will be conducted in early 1997. Important capabilities for observatories which do not presently exist include: cross-hole seismic experiments, which can reveal structural heterogeneity not obtainable from single holes, cross-hole permeability experiments, and selective sealing of portions of the borehole, in order to sub-divide the area being monitored.

Recommendations for implementation

Instrumented boreholes provide a strategy that is of interest to several different research initiatives. The technological aspects of instrumenting boreholes are already being discussed by the planners of the Ocean Seismic Network (ION?), and have recommended that ODP establish a Borehole Instrumentation Program Planning Group (PPG), with which we concur. It is recommended that an ODP DPG on Ridge Axis Borehole Observatories be called, which is given oversight by (or liaison to) the Borehole Instrumentation PPG, in order to both avoid duplication of effort and consider the more diverse technologies (i.e., not just seismometers) required for the ridge observatory experiment. InterRidge and several of the member RIDGE programs are already pursuing seafloor observatories, primarily using seafloor deployed instrumentation, so it is essential that efforts to establish borehole observatories in ridge settings be coordinated entirely with those efforts. This is probably most effectively accomplished by a liaison between the DPG and the InterRIDGE Active Processes Working Group. Proposals to initiate a Juan de Fuca seafloor observatory are being submitted August 1996, and the success of these proposals will have important consequences for site selection of a more permanent installation that might include boreholes.

By its very nature, the observatory concept, especially localized around an active hydrothermal vent community, is multi-disciplinary in nature and involves a large component of the marine community, so creating broad support for this program should not prove challenging. The most difficult aspect will be reaching community consensus on a specific site, which will be largely determined by the primary ridge observatory framework to which borehole observatories will be coupled.

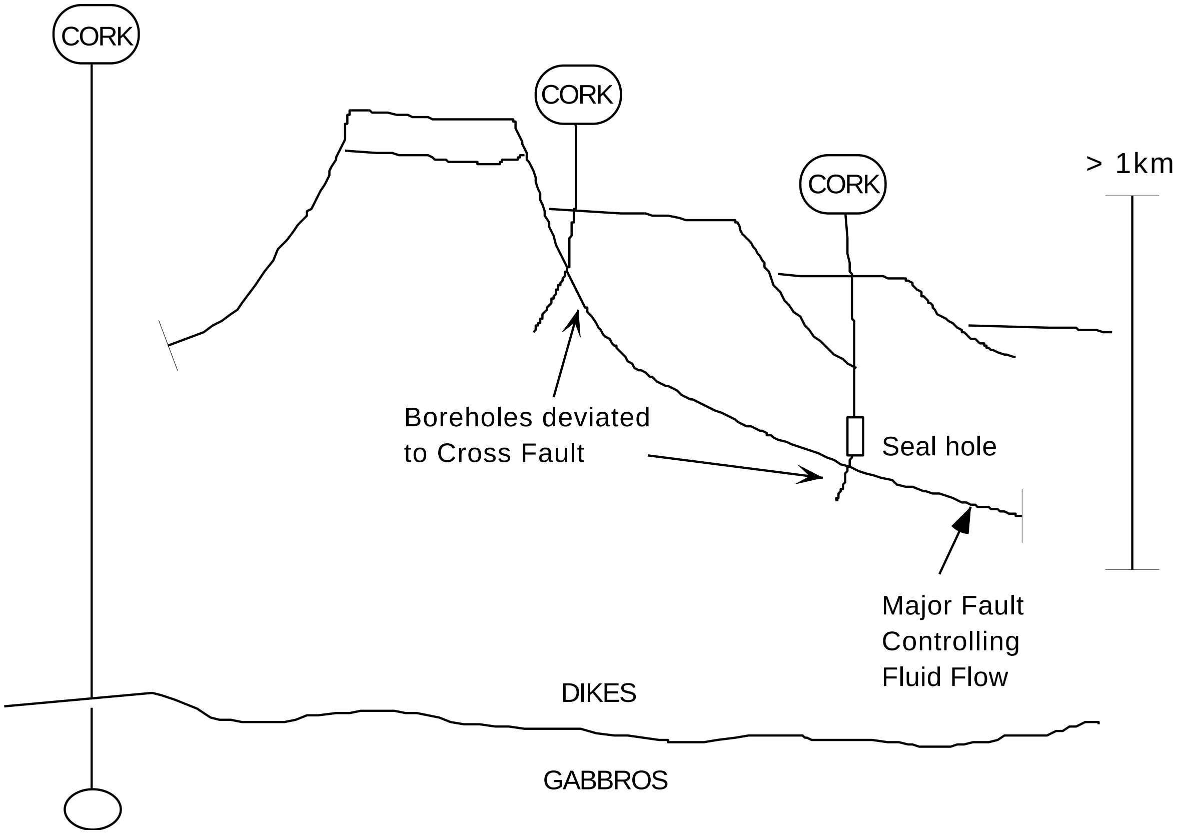


5 holes initially ~500 m deep; at least 1 hole deepened to ~2 km

Phase III: Stage 1 - drill holes 1, 2, 3 and CORK
Stage 2 - drill holes 4 & 5 and CORK

Phase IV: Stage 3 - deepen one hole to ~2 km

Section 4.3, Figure 1: Ridge Axis Borehole Observatory Experiment



Section 4.3, Figure 2: Rise Flank Observatory Experiment

4.4 - LARGE IGNEOUS PROVINCES WORKING GROUP REPORT
Cretaceous LIPs: Mantle Overturn and Environmental Consequences

Participants: N. Arndt, C. Büecker, G. Brugmann, P. Castillo, D. Christie, M. Coffin, R. Duncan, O. Eldholm, G. Ito, P. Janney, P. Johnson, P. Kelemen, E. Kikawa, L. Kroenke, H. Lapierre, J. Ludden, J.O'Connor, M. Pringle, W. Sager, D. Weiss, B. West
Additional comments provided after the meeting by: J. Mahoney, M. Richards, and J. Tarduno.

Executive summary

Large igneous provinces (LIPs) are voluminous emplacements of mafic rock not clearly explained by the plate tectonics paradigm. LIPs provide the strongest evidence that at specific times in the past, energy transfer from the Earth's interior to its surface has occurred in a manner substantially different from modern plate tectonics processes. These provinces form the largest expressions of transient basaltic volcanism on Earth, and emplacement rates of the largest provinces may have exceeded the global integrated mid-ocean ridge production rate over time periods of roughly a million years. Furthermore, LIPs may have been important contributors to crustal growth and continental stabilization throughout Earth history.

The Cretaceous period (144-65 Ma) is marked by voluminous and episodic basaltic magmatic events generated from the mantle, and these events appear to correlate with extreme states or rapid changes in the oceans, atmosphere and biosphere. These Cretaceous LIPs are associated with high average global temperatures; high sea level; punctuated episodes of oceanic anoxia; several mass extinctions; a long normal magnetic polarity chron; apparently significant relative motion between Atlantic and Pacific hot spot groups; and possible increased rates of seafloor spreading. Although only 180 m.y., or <5% of Earth history is recorded in the ocean basins, it is sufficiently long to document a dramatic change in the Earth's mode of energy transfer from the Cretaceous, dominated by widespread intraplate volcanism and high spreading rates, to the Cenozoic, which is characterized by limited intraplate volcanism and lower spreading rates. Age correlations between LIPs and environmental parameters raise the strong possibility of solid earth causal mechanisms. Through ocean drilling, we seek to better understand the timing, genesis, and environmental effects of voluminous and episodic mafic magmatism during the Cretaceous, when mantle dynamics and crustal accretion were markedly different from those of the Cenozoic era.

Our specific scientific objectives address fundamental Earth problems. First and foremost, we must determine the chronology of individual LIP emplacements as well as the timing of all LIPs during the entire Cretaceous period. Determination of source composition, melting regime, and melt migration is critical for understanding asthenospheric and lithospheric geodynamic processes. The tectonic setting and deformational history of LIP emplacement must be defined so that the interaction between LIPs and plate tectonics can be better understood. Finally, the impact of Cretaceous LIP emplacements on the biosphere, hydrosphere, and atmosphere is potentially significant and should be fully investigated by drilling proximal and distal sites with detailed sedimentary records.

Approximately twenty oceanic plateaus, volcanic passive margins, and continental flood basalts were emplaced during Cretaceous time. Two of these LIPs, Ontong Java and Kerguelen plateaus, are giants, each covering an area of ~2 x 10^6-km^2, or approximately one-third the size of the contiguous United States. To meet our scientific objectives, exploratory drilling and associated geophysical investigations of these two features are necessary. In addition, other members of the Cretaceous LIPs family, both older and younger, must be surveyed and drilled to address key LIP issues. The preferred, focused LIP drilling strategy is for one leg on the Kerguelen Plateau/Broken Ridge prior to the end of Phase II; three legs (Ontong Java, an older plateau, and a younger plateau) during Phase III; and one deep (Ontong Java or Kerguelen) and two intermediate depth holes during Phase IV.

Implementation of our drilling strategy will be enhanced by formation of a LIP Working Group within the ODP system. We advocate that JOIDES closely liaise and consult with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Large-Volume Basaltic Provinces in forming such a group.

Phases II and III will involve exploratory drilling of Cretaceous LIPs using existing technology aboard *JOIDES Resolution*. New technology will be needed for the deep and intermediate depth holes required in Phase IV. The necessity of appropriate crustal and mantle geophysical surveys on Cretaceous LIPs must be emphasized; integration of these geophysical data and drilling results is critical to addressing fundamental LIP science objectives.

Scientific rationale

Large igneous provinces (LIPs) are voluminous emplacements of mafic rock not clearly explained by the plate tectonics paradigm. LIPs, comprising oceanic plateaus, volcanic passive margins, and continental flood basalts (Fig. 1), provide the strongest evidence that at specific times in the past, most obviously the Cretaceous, energy transfer from the Earth's interior to its surface has occurred in a mode substantially different from present-day processes (Fig. 2). In fact, large igneous pulses may have occurred repeatedly from Archean to Cretaceous time, but much of the evidence for pre-Cretaceous LIPs is either obscured by collisional tectonics or removed be erosion. LIPs form the largest expressions of transient basaltic volcanism on Earth, and emplacement rates of the largest provinces may have exceeded the global mid-ocean ridge production rate over time periods of roughly a million years. Probable analogs to LIPs are observed on Venus, Mars, the Moon, and possibly Mercury, and the paucity of evidence for plate tectonics on these planetary bodies implies that the Cretaceous mode of abrupt mantle overturn and internal heat loss on Earth is more common and fundamental throughout the solar system than the steady-state plate tectonic mode that we observe on Earth today. Despite the global occurrence and importance of LIPs to the Earth's dynamics, heat budget, chemical differentiation, and environment (Fig. 3), our knowledge of LIPs is rudimentary due to a profound lack of constraining geological and geophysical data. For example, estimates of such basic LIP parameters as ages, volumes, fluxes, composition, and relationship to plate boundary changes are crude for most provinces and unknown in some.

Today, we investigate upper mantle circulation by studying the mid-ocean ridge system, which accounts for ~95% of the mass and heat transfer from mantle to crust. During certain intervals of the Cretaceous period, however, 50% or more of the mantle mass and heat flux may have occurred via emplacement of the ~20 Cretaceous oceanic plateaus, volcanic passive margins, and continental flood basalts (Fig. 1). Therefore, to investigate Cretaceous mantle dynamics, including the state of the mantle before and after individual LIP events, we need to examine the spectrum of Cretaceous LIPs. Through exploratory drilling, the Ocean Drilling Program (ODP) has played a key role in discovering the significance of oceanic LIPs and in defining outstanding scientific problems. Furthering our understanding of oceanic LIPs critically depends on focused ODP investigations employing both existing and new technologies. We seek to describe and understand the upper crustal to upper mantle magmatic, metamorphic, hydrothermal, and deformational processes related to LIP emplacement, to investigate how LIPs relate to deeper mantle processes and dynamics, and to determine how LIPs affect the environment, including the biosphere.

FIRST ORDER SCIENTIFIC PROBLEMS

Four first order problems related to characterization and quantification of mafic igneous crustal production and its effects during Cretaceous time are addressable by ocean drilling. The first problem is to establish a chronology of LIP magmatism between 144 and 65 Ma; the second is to constrain source compositions, melting systematics, and movement of melt; the third is to identify relationships between LIP formation and tectonic processes; and the fourth is to determine the effects of LIP formation on the environment, including the biosphere, hydrosphere, and atmosphere.

1) Chronology of LIP magmatism.

A fundamental distinction between Cretaceous LIPs and modern hot spot volcanism is the rate of melt production. Limited basement samples yield narrow age ranges for individual LIPs and some bimodal age distributions, suggesting catastrophic or episodic volcanic events with magma fluxes significantly greater than those at modern hot spots. In addition, existing age data suggest that many constructional episodes of different LIPs occurred contemporaneously, which results in an apparent episodicity of the global magmatic flux in Cretaceous time. Thus, the primary objectives are to:

a) Quantify volumes and duration of individual magmatic events as well as time-averaged fluxes over the entire period of formation. Did individual LIPs form catastrophically by single massive events, episodically by two or more large events, or continuously by many small events? Such results will allow testing of existing hypotheses of LIP formation. One such hypothesis is that LIPs may have formed by rapid surfacing of plume heads, which resulted in massive flood basalt volcanism. A variant, which may explain episodic construction, is a double plume head scenario in which the initial plume head breaks into two separate heads as it ascends through the viscosity discontinuity between the lower and upper mantle. Another model for episodic volcanism involves initial melting of material from just below the 670-km discontinuity, ascent of material to the mantle solidus caused by mantle avalanches from beneath subduction zones, followed by plume volcanism originating at the core-mantle boundary driven by rapidly sinking slabs. Yet a third hypothesis is that these giant edifices formed relatively continuously by long-lived plume-ridge interactions, such as the modern Iceland-Mid-Atlantic Ridge system. Acquisition of spatially distributed drilling samples in a LIP is required to determine the age range of plateau emplacement. Age information combined with geophysical—seismic reflection, seismic refraction, and gravity—constraints on magma volume, is vital to test these hypotheses and to formulate new interpretations. Furthermore, observations of physical volcanology, such as flow thicknesses and directions, morphology, vesicle distribution, and presence and nature of interbeds, can provide information about the distribution of melt conduits and fluxes.

b) Establish temporal relationships among different Cretaceous LIPs. What is the relative timing of formation of different LIPs, and how might this reflect dynamic processes in the mantle? Are there simultaneities among emplacements of LIPs, or episodicities? Do LIPs reflect the ‘pulse’ of the deep mantle?

c) Quantify LIP contributions to the global magmatic flux throughout the Cretaceous period. To understand geodynamic mantle processes in the Cretaceous, we must determine relationships between magmatic flux and other global processes such as changes in patterns of plate subduction, plate velocities, MORB compositions (e.g., appearance of Dupal anomaly), true polar wander, motion between Atlantic and Pacific hot spot groups, and magnetic reversal frequencies.

2) Source composition, melting regime, and melt migration.

Massive decompressional melting of mantle, whether initiated by plumes originating at boundary layers within the Earth, by lithospheric plate separation, or from extraterrestrial impacts, is required to make LIPs. Important, but poorly known aspects of LIP formation include the thermal regime, history of melt production and migration, the relative contributions of various mantle sources, and related hydrothermal metamorphism. Horizontal and vertical sampling of LIP stratigraphy will provide requisite compositional data to:

a) Determine compositional ranges of LIP extrusive and intrusive rocks. This information can be inverted to estimate composition, extent of partial melting, temperature, and pressure of the asthenospheric source and lithosphere, as well as magma migration mechanisms and plumbing systems. Because parental magmas of basalts in various models originate at different mantle depths and follow different time-temperature paths, petrological and geochemical studies of basalts and intrusive rocks, combined with estimates of magma production rates, will provide insight into the causes of anomalous melting. It is important to sample both extrusive and intrusive LIP rocks to fully assess melt generation, accumulation, fractionation, migration, and evolution histories, through which the thermodynamic, compositional, and metamorphic development of lithosphere-asthenosphere interactions can be constrained.

b) Determine spatial distributions of compositions and compositional gradients. Such systematics may reflect the size of the melting region, source mixing processes, and temporal variability of melts. Because LIPs probably contaminate the MORB reservoir, compositional studies should eventually yield a time scale for mixing in the upper mantle.

3) Relationships between LIPs and tectonics.

LIPs are emplaced in tectonic environments ranging from purely extensional to intraplate. Some controversy exists as to whether changes in plate motion, especially continental breakup, are the cause of most LIPs, or whether LIPs are a major influence on plate motions changes. The temporal relationship between LIP emplacement and plate boundary changes is critical but unclear, especially for the two giant Cretaceous LIPs, Ontong Java and Kerguelen (Fig. 4). In some instances, Cretaceous LIPs (e.g., Shatsky, Paraná/Etendeka) are close in age to adjacent oceanic crust, implying that LIP formation, seafloor spreading, and continental breakup might be related in some way, which is clearly the case with volcanic margins. Some LIPs (e.g., Manihiki, Kerguelen) are extensively deformed by normal faults, suggesting that post-emplacement tectonics may be important in shaping morphology. Currently at least one oceanic plateau (Ontong Java) is being obducted to form part of an island arc, and two others (Caribbean and Wrangellia) form accreted terranes in mountain belts. Many continental nuclei are Archean greenstone belts, which have been proposed to be unsubducted oceanic plateaus. Knowledge of the composition, density structure, and hence buoyancy of LIPs, to be gained in significant part through ODP, will further our understanding of the role of LIPs in continental growth and also in the generation of much of the Earth's mineral wealth. To determine relationships between LIP formation and tectonics during and subsequent to emplacement, we must:

a) Determine stratigraphic and structural relationships between LIPs and adjacent oceanic crust, and within individual LIPs. Combined seismic and litho-stratigraphy can reveal temporal and spatial patterns of LIP emplacement in a regional tectonic framework, as well as test for synchronous or asynchronous post-emplacement tectonism of the LIP and adjacent ocean basin(s). Stratigraphic and structural analyses within individual LIPs have the potential to reveal relationships between tectonic events and magmatic episodes.

b) Establish spatial, temporal, and compositional relationships between LIP magmatism and magmatism at spreading ridges. What are the relationships between the formation of LIPs and changes in plate boundary geometry, seafloor spreading rates, plate motion, and oceanic crustal compositions? Such plate boundaries include continental rifts, mid-ocean spreading centers, triple junctions, and transform boundaries.

c) Determine vertical and horizontal tectonic histories. Such information, recorded in overlying sediments and in the physical volcanology (whether submarine or subaerial), reflect mantle upwelling, crustal thinning, lithospheric thermal histories, crustal growth histories, and post-emplacement subsidence and faulting. Uplift histories can constrain LIP emplacement models. Some LIPs (e.g., Kerguelen, East Greenland) have subsided similarly to cooling oceanic lithosphere or rifted lithosphere, whereas others (e.g., Ontong Java, Caribbean) have not. Is LIP lithosphere thermally rejuvenated by post-primary magmatism? Are the boundaries of LIPs zones of lithospheric weakness that can be readily reactivated by changing stress patterns in the ocean basins?

4) Environmental impact: biosphere, hydrosphere, and atmosphere.

Cretaceous oceans were characterized by global variations in ocean chemistry, relatively high temperatures, high relative sea level, episodic deposition of black shales, high production of hydrocarbons, and mass extinctions of marine organisms. Intense pulses of igneous activity associated with transient LIP emplacement affect the physical and chemical character of the mantle, oceans, and atmosphere to an undetermined extent, and may have significant effects on the biosphere. Tentative temporal correlations of Cretaceous pulses and rates of LIP formation with major environmental changes require further analysis to define linkages and causes. Ocean drilling will help to evaluate potential causal relationships between LIP formation and environmental events by addressing the following problems:

a) Effects on the hydrosphere and atmosphere. Submarine and subaerial volcanism have substantially different effects on the Earth's environment, yet the emplacement environments for many Cretaceous LIPs are unknown. Once drilling and geophysical results establish submarine/subaerial volcanic ratios for individual LIPs and volatile contents for lavas are determined, fluxes of volatiles, particulates, and heat from LIPs into the atmosphere-hydrosphere-biosphere system can be estimated and their environmental impact can be assessed. Ocean drilling is critical for determining precise temporal relationships between LIP emplacements and changes in environmental parameters (e.g., $^{87}Sr/^{86}Sr$ in sea water, black shale 'events', mass extinctions, sea level), and for providing insight into possible threshold levels for the LIP 'impacts'.

b) The role of hydrothermal and metamorphic processes. What are the chemical fluxes, depths, spatial distribution, geometry, and alteration processes of hydrothermal circulation and metamorphism at LIPs? The thermal and permeability structure of old oceanic and transitional crust invaded by LIP heat sources likely differs from mid-ocean ridges. Therefore, the products and consequences of hydrothermal activity and metamorphism in this setting may differ significantly from the spreading ridge environment. Gradients in trace metals resulting from hydrothermal activity may “fingerprint” each LIP and enable precise correlation with global oceanic anoxic events.

A drilling strategy for oceanic LIPs

LIPs are enormous igneous constructions that present considerable challenges for adequate sampling to address our first order questions. Our knowledge of these features is rudimentary, similar, perhaps, to that of mid-ocean ridges prior to general acceptance of the plate tectonics paradigm in the late 1960s. Considerable shallow basement drilling as well as significant geophysical surveying are necessary to begin to address issues of Cretaceous mantle dynamics and environmental consequences. At some future time, deep (>2000 m) drilling on LIPs will be vital for elucidating the density structure and composition of middle to lower crust beneath LIPs. The LIP drilling strategy described below represents a refinement and further evolution of thought from strategies previously outlined by Coffin & Eldholm (1991); JOIDES Lithosphere Panel (1994); ODP Long-Range Plan (1996); Intraplate Marine Geoscience: Hot LIPs and Cracked Plates (1996).

Understanding the complete temporal and compositional history of features of this scale will require a variety of approaches in several opportune locations. In Figure 3 we have summarized these sampling approaches. Seismic imaging of oceanic LIPs has revealed several common features: crustal thickness varies from that of normal oceanic lithosphere to greater than five times that in extreme cases. Volcanic sections, commonly lying beneath sediments several 100s to 1000s of meter thick, range from a few kilometers to possibly 10-km thick. Lava flow sequences commonly exhibit a strong fabric of dipping reflectors in seismic profiles, indicating a temporal sequence related to eruption location and magma supply. Internal reflectors and velocity structure indicate the presence of thick sections of higher density material, probably mafic sill complexes, cumulate layers, and ultramafic bodies.

A significant sampling of the total igneous stratigraphy using current drilling capabilities can be obtained by a combination of several strategies:

1) *Transects* of shallow (~200 m) basement holes across the surface of the LIP over crust of varying thickness, i.e., from feather-edge to LIP center, guided by temporal relations indicated in dipping reflector sequences.
2) *Offset drilling in tectonic windows* that expose deep levels of the LIP otherwise inaccessible. These sites occur at tectonized margins or interiors of many LIPs and must be well-characterized by geophysical and submersible surveying and surface sampling.
3) *On-land sections* of obducted portions of LIPs or of autochthonous LIPs along volcanic passive

margins provide opportunities for detailed sampling of parts of the stratigraphy. In most instances, however, it is difficult to relate these tectonized sections to the intact (submarine) portions of the LIP by geophysical methods.

4) *Reference holes* address three important components of our LIP sampling strategy: (1) Samples are needed to establish the age and composition of the older plate on which some or all of the LIP is built, in order to properly assess the effects of lithospheric contamination on the LIP compositions, to evaluate pre-LIP asthenospheric mantle compositions, and to model uplift and subsidence of the LIP. (2) The sedimentary section on older adjacent crust records the near field environmental impact of the LIP emplacement. (3) debris shed from the LIP during construction accumulates in sedimentary aprons on the old plate, providing a means of establishing the volcanic history.

5) *Holes of opportunity* involve penetrating basement to bit destruction whenever any ODP hole is within reach of basement on any LIP. Basement samples from such holes will provide age and compositional data for the LIP, data which do not exist for the overwhelming majority of submarine LIPs.

To assess the range of environmental responses to LIP formation, we require sampling of the hydrothermal fields and metamorphic zones to determine fluid compositions from alteration effects, and timing and scale of discrete events. Effects can also be observed in high resolution sedimentary sections drilled in the near- and far-field, e.g., on topographic highs such as older plateaus or seamounts.

All basement drill holes in LIPs should be logged. In cases of poor core recovery or loss, only downhill logging can provide critical information on physical and chemical properties of formations penetrated by the borehole. Furthermore, the state of stress, and dynamic parameters such as permeability, temperature, and pressure can be determined from spatially discrete data acquired by down hole tools.

It must be emphasized that no one LIP can address every major scientific LIP issue. A family of LIPs, therefore, must be investigated. The two most voluminous LIPs known, the Ontong Java and Kerguelen plateaus, are both Cretaceous in age. It is of the highest scientific priority to first investigate these two provinces, which may provide both the strongest insights into Cretaceous mantle dynamics and into the environmental impact of LIP formation. We also strongly advocate drilling one Cretaceous LIP older than the two giant plateaus, and one Cretaceous LIP younger than the two giants. The older LIP will enable assessment of Early Cretaceous LIP basalt compositions and eruption rates prior to the largest basaltic volcanism episodes, as well as provide a sedimentary record of environmental changes prior to, during, and subsequent to the formation for the giant plateaus. The younger LIP will provide important information on massive basaltic volcanism occurring in many locations throughout the world between 85 and 90 Ma.

Our recommended specific strategy for Phases II, III, and IV of the Ocean Drilling Program, consistent with Table 1, is:

Phase II - one leg on Kerguelen Plateau, including one site on Broken Ridge

Phase III - three legs: one on Ontong Java Plateau, one on an older plateau (e.g., Shatsky); one on a younger plateau (e.g., Caribbean)

Phase IV - two intermediate (1000 to 2000-m into basement) holes; one deep (>2000-m into basement) hole on one of two giant LIPs

Implementation

WORKING GROUPS

We recommend that a “Large Igneous Provinces” Program Planning Group be constituted to provide advice within the Ocean Drilling Program planning structure on issues related to scientific ocean drilling of large-volume basaltic provinces. Such a PPG would ideally consist of ~15 members drawn from appropriate disciplines, including, but not necessarily limited to volcanology, geochronology, petrology, geochemistry, geophysics, geodynamics, oceanography, paleontology, paleomagnetism, planetology, and climatology. The LIP PPG would include proponents from all active LIP proposals in the JOIDES system.

COORDINATION WITH GLOBAL INITIATIVES

In 1992, the International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI) initiated the Commission on Large-Volume Basaltic Provinces. IAVCEI is a member of the International Union of Geodesy and Geophysics (IUGG), which in turn is part of the International Council of Scientific Unions (ICSU). The Commission on Large-Volume Basaltic Province’s main missions are to encourage and promote interest in and research on large-volume basaltic provinces; to foster interchange of ideas and relevant data among earth scientists; and to maintain and distribute up-to-date bibliographic data bases and compendia of active research projects. Since the Commission’s founding, it has grown to include ~500 members from five continents. The commission’s activities are guided by a steering committee consisting of ~20 members.

Given the broad expertise, widespread community involvement, and international composition of IAVCEI’s Commission on Large-Volume Basaltic Provinces, we recommend that the Ocean Drilling Program consult closely with the Commission in filling membership on a JOIDES “Large Igneous Provinces” working group.

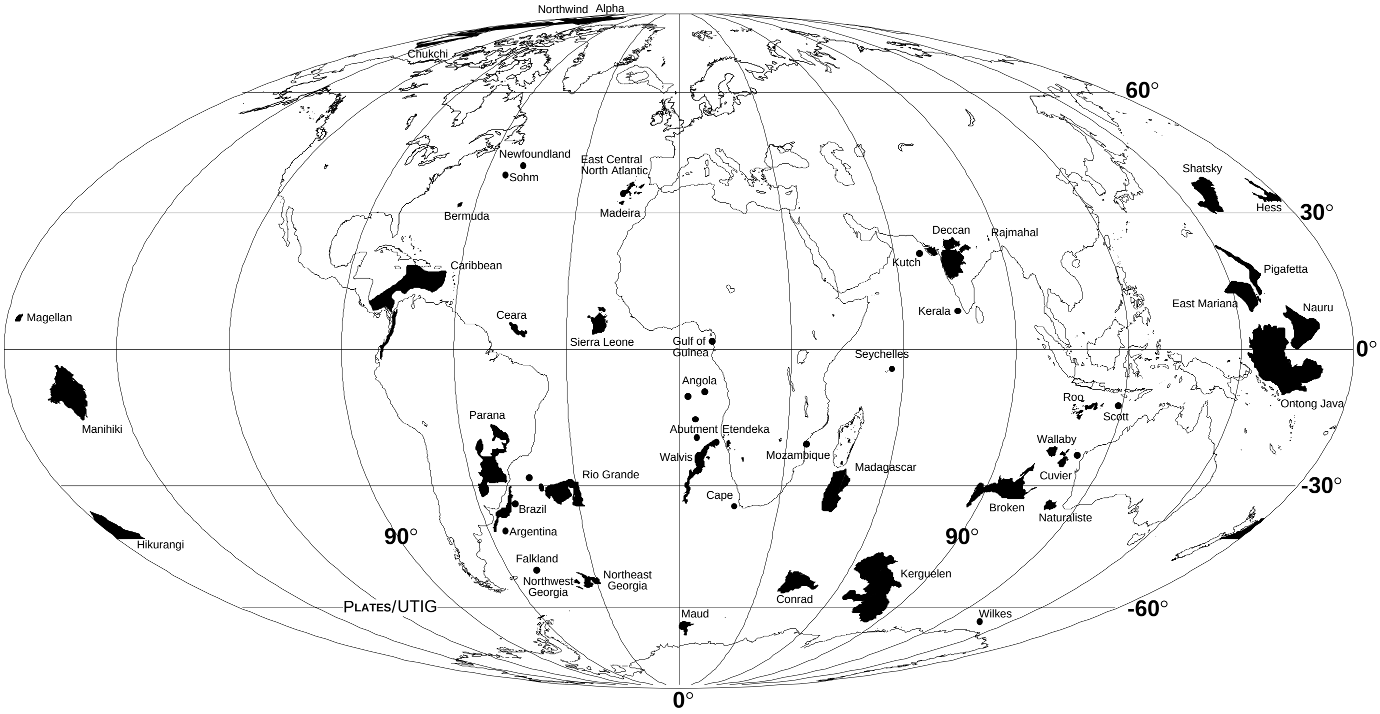
Technological requirements

Previous drilling of volcanic margin LIPs has proven the feasibility of drilling thick volcanic sequences with reasonably good core recovery (legs 104, 152, 163). In fact, the *JOIDES Resolution*’s full capabilities for LIP basement penetration have not yet been tested, because drilling ceased at the two deepest volcanic margin basement sites (642 @ 914 m; 917 @ 779 m) due to time limitations and achievement of objectives, and not to technical difficulties or technological limitations. Furthermore, it has been shown that integration of core and log data allows the construction of a complete, detailed lava stratigraphy.

The exploratory phase of shallow (≤200 m) basement LIP drilling during Phase II and Phase III (1998-2003) does not require new technologies or platforms. It is expected that knowledge gained during Phase III, however, will provide essential information for identifying sites for deep drill holes in Phase IV and beyond. New drilling technologies will be needed to penetrate deeply into LIPs to recover complete stratigraphic sections through oceanic LIPs. These drill holes will allow recovery of both the extrusive and intrusive igneous layers of LIPs,, thus, constraining temporal, compositional, structural, and metamorphic evolution of emplacement.

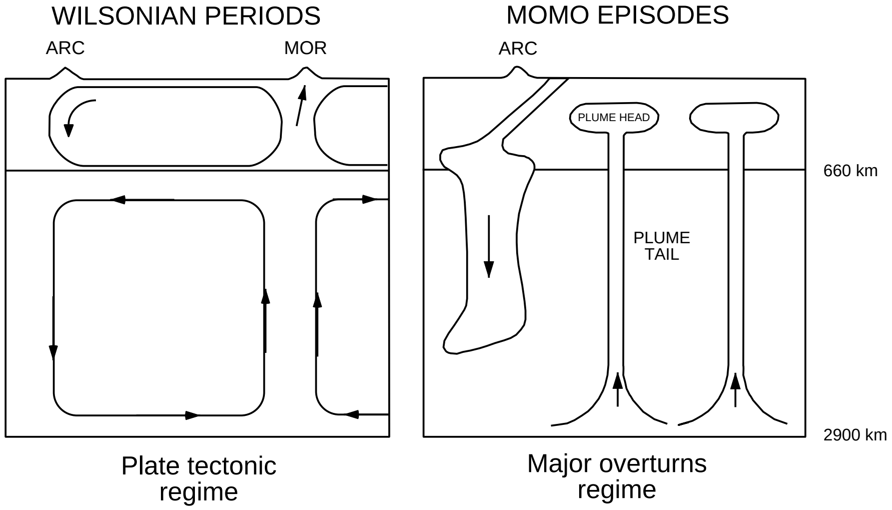
The recent recognition of the importance of LIPs in earth history has not yet developed into many ODP proposals. Of approximately 20 Cretaceous LIPs, mature proposals for four have been submitted as of June 1996, and one of the two critical LIPs, the Ontong Java Plateau, lacks necessary site survey data. The possibility of LIP drilling becoming a significant component of ODP Phases III-IV should be made known to the scientific community in the form of soliciting Phase III proposals.

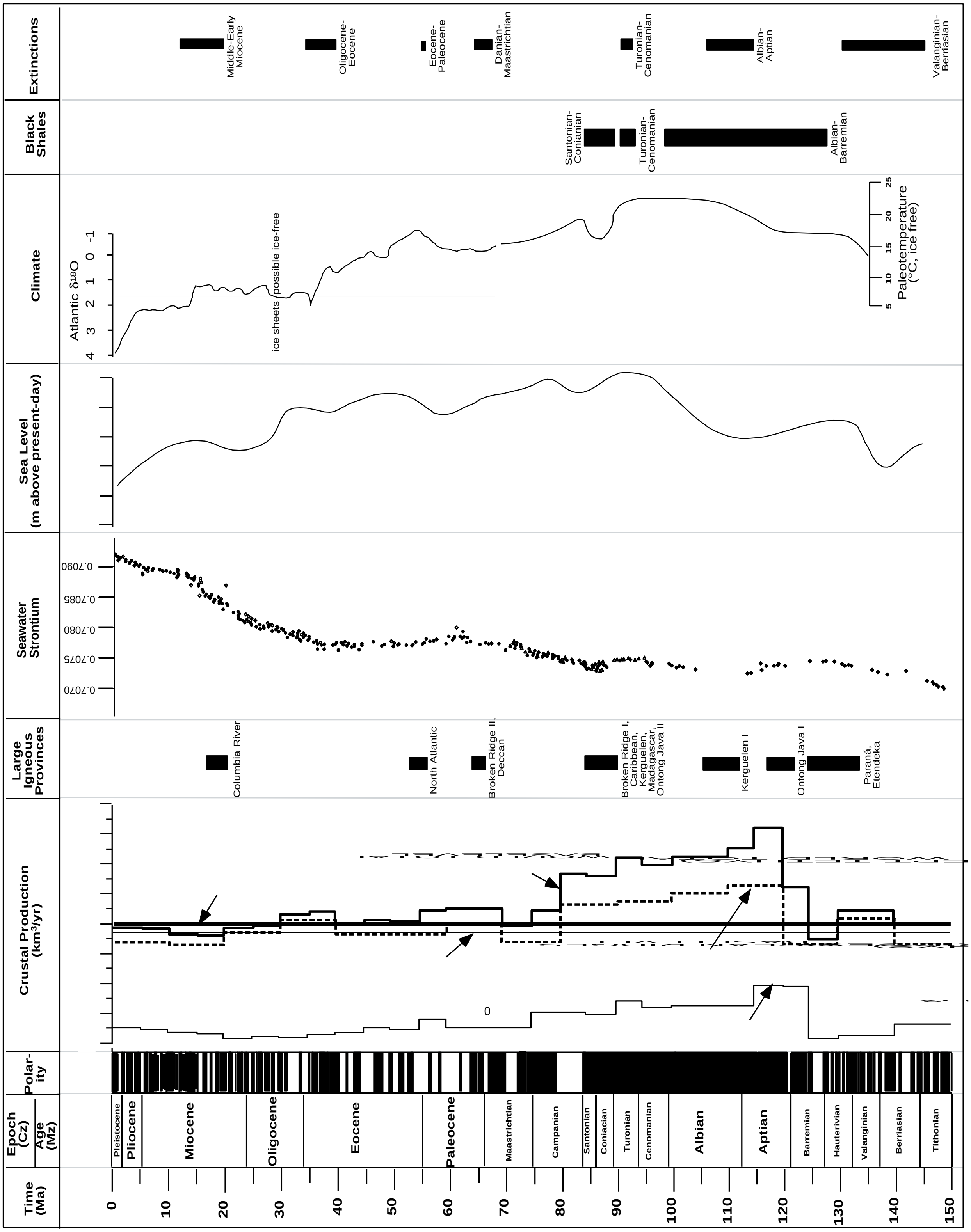
With the exception of some volcanic margins, most LIPs are currently poorly surveyed by geophysical techniques. It is therefore of utmost importance that additional geophysical surveys be undertaken. In particular, there is need for geophysical exploration of the giant Ontong Java Plateau, where drilling requires new regional studies followed by detailed site surveying. We urge ODP member nations to support surveying of this kind.



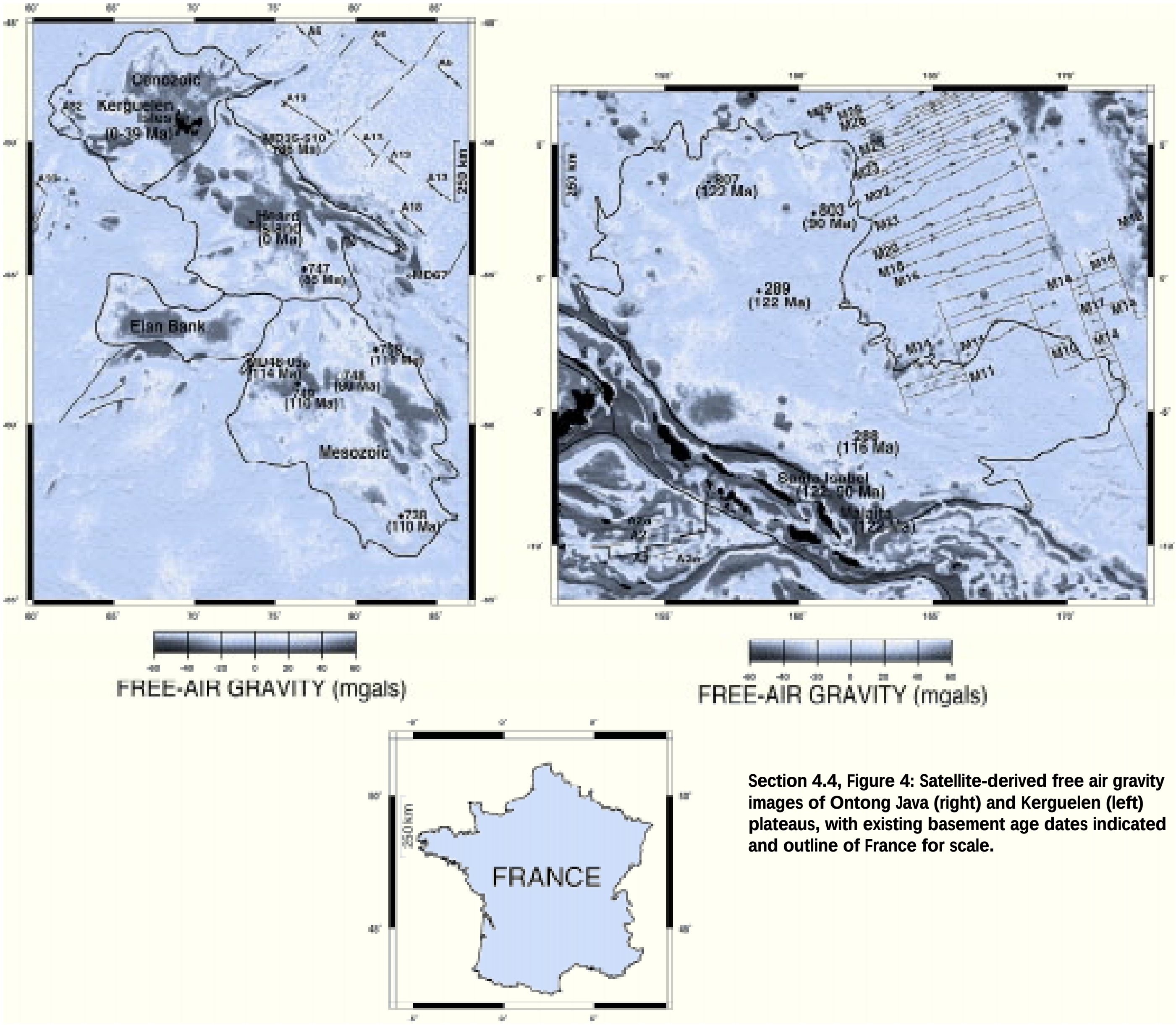
Section 4.4, Figure 1: Transient Cretaceous LIPs (polygons), both documented and assumed, including volcanic passive margins and anomalous seafloor spreading crust (circles).

Section 4.4, Figure 2: Model of Wilsonian periods and MOMO (mantle overturn, major orogeny) episodes. During Wilsonian periods (left), the normal mode of plate tectonics prevails, with opening and closing of oceans, and mantle convection with isolated upper and lower mantle. Plumes originate predominantly from the base of the upper layer, and continental growth is dominated by arc accretion. During MOMO episodes (right), accumulated cold material descends from the 660-km boundary layer into the lower mantle, and multiple major plumes rise from the core-mantle boundary to the surface,, thus, creating a major overturn. Large plume heads create oceanic plateaus, some of which may be converted to juvenile continental crust by lateral accretion, or underplate existing continental lithosphere and crust.

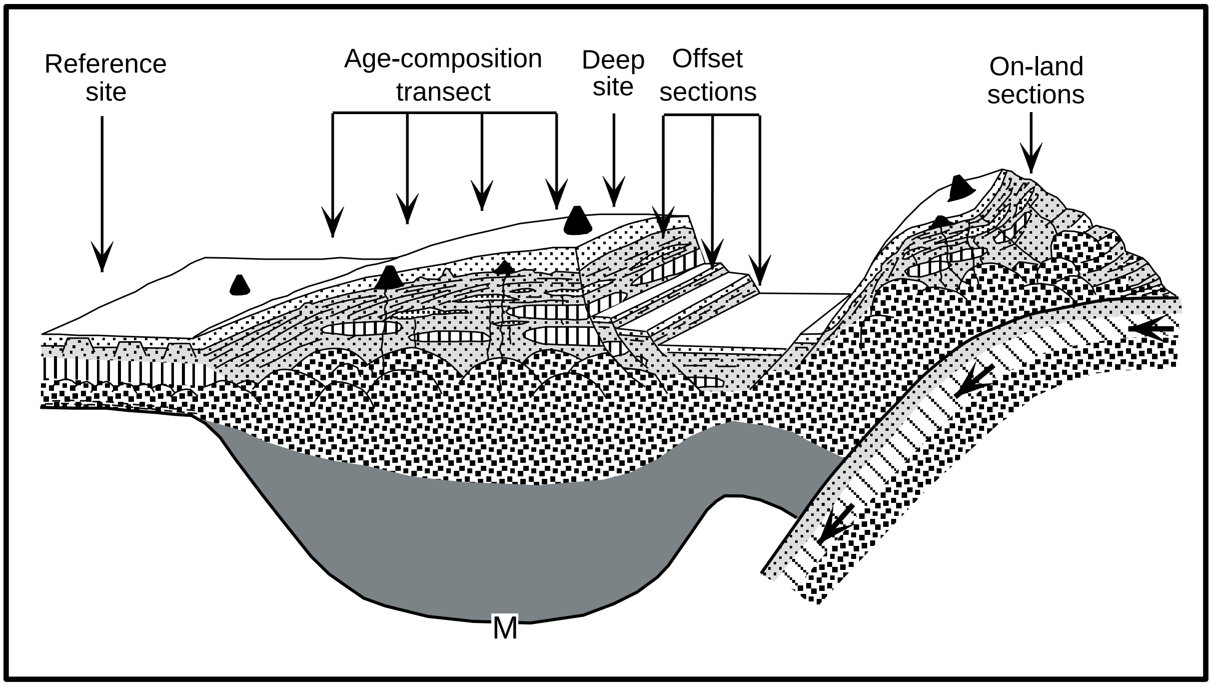




Section 4.4, Figure 3: Temporal correlations among geomagnetic polarity, crustal production rates, LIPs, sea water Sr, sea level, climate, black shales, and mass extinctions.



Section 4.4, Figure 4: Satellite-derived free air gravity images of Ontong Java (right) and Kerguelen (left) plateaus, with existing basement age dates indicated and outline of France for scale.



Section 4.4, Figure 5: Proposed LIP drilling strategy. Age-composition transect sites penetrate ~200-m into volcanic basement, with intermediate and deep sites to be chosen following exploratory drilling. Offset sections provide windows into middle and deep crustal levels. On-land sections permit detailed sampling, albeit of tectonized rocks. Reference sites on older oceanic crust record the volcanic and deformational history of LIP emplacement.

4.5 - CONVERGENT MARGINS WORKING GROUP REPORT
Evolution of Oceanic Lithosphere at Convergent Margins

Participants: Dick Arculus (WG chair), Pamela Kempton (Steering Committee rep), Yildrem Dilek, Tim Francis, Brent McInnes, Hazel Prichard, Kensaku Tamaki, Brian Taylo and Rob Zierenberg.

Introduction

Subduction of oceanic lithosphere plays a fundamental part in global plate tectonic and mantle convection cycles. It is arguably the primary contributor to the global chemical flux between the lithosphere and mantle, and is the principal means by which lithospheric and entrained exospheric material is (re)cycled into the mantle. Long-term, global chemical differentiation of the Earth occurs at convergent margins through several mechanisms including material that fails to subduct and is accreted to or subcreted beneath the fore-arc, and/or a combination of fluid/melt transfer from subducted lithosphere that triggers melting in the overlying asthenosphere and lithosphere. All of these processes ultimately contribute to the growth of continents. This is a first order and continuing process within the Earth, equivalent in terms of cumulative chemical impact with the formation of the core some ~ 4.5 Ga ago.

In spite of the tremendous progress made from studies of convergent margins over the past 40 years, including major contributions from the DSDP and ODP (for a review, see Taylor and Natland, 1995), fundamental first order problems remain that are particularly relevant to lithospheric formation. For example, how is subduction initiated and how do island arcs originate and evolve? What is the relationship between suprasubduction zone environments and ophiolites? What are the mantle dynamics associated with the transition from rifting to true ocean spreading in the back-arc environment? What processes operating in active convergent margins contribute to, or provide appropriate environments for, concentrating metals in massive sulfide deposits, particularly those which may be analogues for some of the larger, economically significant world-class precious and base metal deposits?

The breadth of these problems encompasses more than the interests of the oceanic lithosphere community. Indeed, the interests of the working group on “Evolution of Oceanic Lithosphere at Convergent Margins” lie at the interface between the oceanic lithosphere and the continental margins communities. The Long Range Plan of the ODP identifies the understanding of global geochemical recycling as one of the major tasks ahead, and resolution of these issues requires a range of studies at convergent margins, including spatial and secular geochemical evolution of arc systems and the determination of fluxes at accretionary/non accretionary prisms. There are also clear overlaps of interest between these various groups of scientists and those currently involved in the planning and execution of studies in back-arc basins through InterRidge.

As an immediate priority, we recommend that the ODP planning structure establish a **Program Planning Group on Active Convergent Margins** to develop and coordinate the drilling plans of these different groups. In the interim, our conclusions are focused on drilling goals that are most directly relevant to the oceanic lithosphere community, and of broad significance to the wider geosciences. These goals are:
1. Testing the ophiolite model, and
2. Understanding hydrothermal processes and formation of ore deposits.

Testing the ophiolite model

SCIENTIFIC RATIONALE

The sheeted dikes in ophiolites and the abundant structural evidence for synmagmatic normal faulting provide compelling arguments for their formation by seafloor spreading. Hence, ophiolites are typically assumed to reflect the structure and stratigraphy of oceanic crust formed at mid-ocean ridges. However, it has been known for a number of years that several of the large, relatively intact Tethyan ophiolites such as the Troodos in Cyprus or the Semail in Oman differ in significant respects from the mafic crust formed at mid-oceanic spreading centers. In particular, systematics of the geochemistry of the magmas that formed these ophiolites clearly requires that the parental melts were generated above a subduction zone. This recognition has demanded a radical reappraisal of the use of the majority of the world's ophiolites as direct analogues for oceanic lithosphere formed by spreading at mid-ocean ridges. Unfortunately, this reappraisal has apparently not permeated far into the general geoscience community.

Appropriate modern analogues for supra-subduction zone ophiolites have been difficult to find, especially as their subsurface characteristics are only accessible through drilling. Back-arc basins have provided the most appealing analog, but ophiolites rarely have an associated remnant or active arc, nor are they covered by volcaniclastic sediments shed from those arcs, as is the case for most crust formed in a back-arc basin. Efforts by the DSDP and ODP at the convergent margins of the western Pacific have identified clear alternatives.

We now know from numerous land- and marine-based studies of convergent margins that a range of processes - including rifting, seafloor spreading, under-, intra- and over-plating - contribute to lithospheric growth in zones of tectonic plate convergence. Deep ocean drilling of the Izu-Bonin-Mariana system, for example, has shown that the nascent stages of growth from ~ 48 to 35 Ma were accompanied by major suprasubduction zone extension and formation of new lithosphere with a surface area comprising some ~ 3000-km strike length by ~ 300-km across-strike width (see Taylor, 1992). The rock types characterizing this early extensive phase were boninite and low-K tholeiitic rocks (Pearce et al., 1992) and fractionated derivatives. Subsequent restriction and apparent focusing of magma supply to a narrow outlet termed the 'volcanic front' in the Izu-Bonin-Mariana system represents a transition from seafloor spreading to a different style of lithospheric growth, clearly involving over- and intraplating. Underplating of mafic materials and selective removal during advective erosion by the asthenospheric mantle wedge of both mafic and ultramafic complements of erupted, fractionated magmas is also probable, but not demonstrated. The underlying tectonomagmatic controls governing the transition from the early, seafloor spreading to the 'mature' mode of lithospheric growth at convergent margins are not clearly understood and desperately need further study, including new drilling initiatives.

One of the prominent successes of ODP drilling in the Izu-Bonin-Mariana system was the intersection at Site 786B in the Bonin fore-arc (Fig. 1) of ~ 700-m of volcaniclastic rocks, pillow lavas, and dikes overlying a sheeted dike complex dominated by boninite and tholeiitic rock series (Fig. 2). This recovery was achieved within 14 days of single rotary cone bit drilling. A number of studies (see Fryer, Pearce, Stokking et al., 1992, for summaries) have documented the tectonic and structural history (including subsidence) of this site, and the petrogenesis of the rock suites, documenting the close parallels with major ophiolite bodies. Subsequently, Alt et al. (1996) have also demonstrated a close analogy of stable isotopic systematics (O and S) and alteration style at Hole 786B with those characteristic of the Cyprus and Oman ophiolites. Confirmation of the equivalence of the supra-subduction sequence recovered at

Hole 786B with ophiolites representing a significant fraction of the continental lithosphere is of major interest to a wide geoscience audience.

POSSIBLE GOALS

One possible location for testing the ophiolite model is a return to Site 786 to attempt recovery of a deeper section of crust from the sheeted dike complex, and penetration of the dike feeder zone to the mafic and ultramafic crustal units of layer 3, representing plutonic equivalents of the volcanic and hypabyssal rocks. The composition and petrogenesis of the units, alteration style and mineralogy, and physical properties of recovered rocks - accompanied by a comprehensive, down-hole logging program - can be correlated to at least the shallower components of the remarkably detailed crustal velocity structure obtained across the Bonin arc at the latitude of Hole 786B (e.g., Suyehiro et al., 1996). The importance of this is that it would contribute some ‘ground-truth’ for geophysical models of lithospheric architecture. The thermobarometric and compositional evolution of magma sources in the upper mantle can be inferred by inversion of the geochemical characteristics of the rock units. Direct comparison of this modeling with the variety of upper mantle-derived, ultramafic rocks recovered by the ODP through drilling of neighboring serpentinite extrusions (e.g., Site 784) trenchward of Hole 786B will constrain melt generation and migration processes in this environment. Of further specific interest, and of relevance to the growth of continental crust, are the specifics of platinum-group element chemistry and Re-Os systematics in these sequences.

DRILLING STRATEGY

Of primary importance is penetration to a depth of at least 2-km proximal to the existing Hole 786. This hole lacks a reentry cone, but of course has all relevant surveys from previous efforts and so drilling should be feasible with currently available technology within Phase III of the Program. A reentry cone should be emplaced for potential deepening of the Site during Phase IV.

Understanding hydrothermal processes

SCIENTIFIC RATIONALE

ODP has made important contributions to our understanding of the genesis of metallic ore deposits through drilling of active hydrothermal systems on seafloor spreading centers. Leg 139 drilled sediment-hosted hydrothermal systems on the Juan de Fuca Ridge in Middle Valley and demonstrated the capability of the Resolution to drill in formations at temperatures approaching 300°C. Penetration of 95-m of massive sulfide mineralization conclusively demonstrated that some seafloor deposits have developed on the scale of economically exploitable on-land ore deposits. Drilling of the TAG hydrothermal deposit on the Mid Atlantic Ridge on Leg 158 significantly advanced our understanding of the complex processes responsible for the compositional heterogeneity of hydrothermal deposits. Recrystallization, brecciation, and fluid mixing due to subsurface entrainment of cold sea water into the hydrothermal system contribute to the formation and evolution of the TAG deposit. This leg also provided the first significant penetration into the high-temperature alteration zone underlying an active massive sulfide deposit. Drilling established that the TAG deposit is similar in tonnage and grade to ophiolite hosted deposits that have been economically exploited in Cyprus and Oman (Hannington et al., in press; Figure 3a).

The processes controlling hydrothermal mineralization at ocean ridge spreading centers are applicable to “Cyprus-type” massive sulfide deposits that are developed in the extrusive section of ophiolites. However, as important as the past contributions have been to investigating seafloor sulfide deposits on spreading centers (and by analogy ophiolite-hosted massive sulfide deposits), there are exciting new opportunities for ODP to contribute to the investigation of the genesis of metallic mineral deposits in a variety of tectonic environments, many of which are analogous to mineral deposits of considerably greater economic importance than ophiolite-hosted deposits. Ophiolite-hosted massive sulfide deposits show a limited compositional range and have been exploited primarily for their copper, and to a lesser extent, zinc contents. Low concentrations of other economically important metals, including Pb, Ag and Au, are a reflection of the low concentration of these elements in the basaltic source rocks. Ophiolite-hosted deposits also tend to have relatively low tonnages and grades relative to other types of massive sulfide deposits (Figure 3b). Therefore, although ridge-crest hydrothermal systems and ophiolite-hosted massive sulfide deposits are important natural laboratories for investigating some of the process leading to ore-deposit formation, these deposits are not significant contributors to the resource base and are of less interest to the economic geology community than other types of massive sulfide deposits.

Throughout the geologic record, volcanic-arc-related hydrothermal deposits are more abundant and are significantly larger and higher grade than ophiolite-hosted deposits (Figure 3). Volcanogenic massive sulfides appear to have formed in a variety of tectonic setting, but initial stages of rifting of either continental or island arc crust appears to be a productive environment for the formation of large ore deposits. volcanogenic massive sulfides deposits are hosted by a variety of rock types ranging from mafic to felsic volcanics and associated syn-volcanic sedimentary and volcaniclastic rocks. Subvolcanic intrusive are important local heat sources in sustaining long-lived hydrothermal systems capable of forming large metal deposits. The diversity of potential source rocks in arc-related environments is reflected in the metal content of the associated hydrothermal deposits, especially in the abundance of minor elements that are concentrated in more evolved igneous rocks. Noranda-type and especially Kuroko-type volcanogenic massive sulfides deposits tend to have higher Cu-Zn grades than ophiolite-hosted volcanogenic massive sulfides deposits and some contain significant resources of Pb, Ag, Au, Sb and other metals. Although back-arc basins make up less than 10% of the world’s ridge system, hydrothermal processes in this environment are not insignificant with respect to the surface environment of the Earth. As noted in the InterRidge workshop report on Back-Arc Basins, CO_2 and CH_4 contents of hydrothermal solutions in the JADE site in the Okinawa Trough (NW Pacific) is about two orders of magnitude greater than those of mid-ocean ridges. Therefore, at least for some volatile components, the mantle discharge from back-arc basins may be no less significant than mid-ocean ridges, despite their much shorter ridge length. The ephemeral nature of magmatic fluids makes investigation of these processes difficult in on-land ore deposits.

The largest, and economically most important, massive sulfide deposits are not directly associated with volcanic rocks, but occur in sedimentary sequences that are typically associated with early rifting of continent or continental margins. The source of fluids for these sedimentary-exhalative deposits is generally thought to be primarily from dewatering of sedimentary basins and often involves high salinity fluids derived from dissolution of evaporites. High heat flow in the rifting environment is thought to provides the driving force for hydrothermal circulation.

The Atlantis II Deep in the Red Sea was the first active seafloor hydrothermal deposit discovered and is still the only known seafloor deposit for which the size and grade have been established to be equivalent to the largest massive sulfide deposits known on-land (Fig. 3). It is also the only known setting where high-temperature, high-salinity fluid/rock interaction can be directly investigated on the seafloor.

Although the geochemical setting of the Atlantis II Deep is similar to many volcanic-hosted massive sulfide deposits, the depositional setting is more analogous to the larger and economically more important sedimentary-exhalative deposits (Zierenberg, 1990) and therefore provides an important drilling target for understanding these important deposits.

Massive sulfide deposits are only one of the ore deposit types associated with arc rocks. Porphyry copper deposits form in subduction environments and are the most economically important source of copper world-wide. Although porphyry copper deposit formation occurs at depths that are not likely to be addressed by oceanic drilling, these systems often drive shallower hydrothermal systems that are also important sources of economic resources. Some of the epithermal systems that produce gold deposits may be related to porphyry copper systems and base-metal and precious-metal-rich vein systems are extensively developed in arc settings. An example is the world class Ladolam gold deposit on Lahir Island in the Tabor-Feni island chain in the New Ireland fore-arc basin. This young deposit contains in excess of 15 million ounces of Au, and is still an active site of hydrothermal discharge. Recent surveys have discovered similar hydrothermal activity offshore associated with alkalic volcanism. Samples recovered from the floor of the Tubaf caldera include a diverse suite of crustal and mantle xenoliths and hydrothermal precipitates the include ore grade Au mineralization (B. McInnes, abstract, this workshop).

The caldera of the Tubaf submarine volcano also contains a hydrothermal field inhabited by chemosynthetic vent fauna. As identified by the InterRidge Back-Arc Basin Working Group Report, the geological isolation of back-arc basins from mid-ocean ridges is an important variable when considering the biological and ecological evolution of vent communities. Several new species of mega-fauna, which were not observed at mid-ocean ridges, have been found in back-arc basins. The chemosynthetic bacteria also show a unique character in each hydrothermal community. There is a great potential for carrying out experiments to monitor the interaction between the hydrothermal flux and the ecosystem in back-arc basins.

In summary, although the investigation of water-rock interactions in normal oceanic crust and drilling in active ridge crest hydrothermal systems have significantly enhanced our understanding of ore forming processes, these settings represent only a fraction of the geological settings that can result in economic accumulations of minerals. ODP has the capabilities to make significant contributions to the field of economic geology, and thereby contribute to the societally important goals of creation of wealth and improvement in the standard of living. Many of the important oceanic drilling targets for advancing our understanding of mineral deposit genesis are associated with continental margins and subduction zone settings. Expanding the investigation of the processes of water-rock interaction to include the diverse tectonic settings that host mineral deposits should be a component of lithospheric drilling in to the next century.

POSSIBLE GOALS

The economic importance of subduction zone related volcanogenic massive sulfides deposits to the availability of metals world-wide argues that research drilling in this environment should be a priority. There are potentially many targets and even though the modern arc environments have not been extensively explored, twenty percent of seafloor hydrothermal systems have been discovered in the western Pacific fore-arc-back-arc systems. Certain aspects of water-rock interaction can not be investigated on normal mid-ocean ridge crust, but must be investigated in an arc setting. One example is hydrothermal alteration and ore-fluid formation resulting from high-temperature interaction of sea water with evolved volcanic rocks. Many volcanogenic massive sulfides deposits, particularly those of the Kuroko district in Japan, are hosted by dacitic to rhyolitic rocks. The higher levels of elements like Pb, Sb, and Ag in these deposits, relative to basalt hosted volcanogenic massive sulfides deposits, indicated that the fluids responsible for ore formation have equilibrated at high temperature with felsic igneous rocks, but the details of water-rock interaction in these systems are less well known. Arc related rocks also have much higher volatile contents than MORB, raising the possibility of direct magmatic input to the ore forming systems. The differences in viscosity and buoyancy between felsic and mafic lavas may also lead to important differences in the emplacement of evolved volcanic rocks on the seafloor, which could change the porosity/permeability structure of the crust, thereby leading to different controls on hydrothermal circulation. Investigating any of these processes requires access to the subsurface environment in active hydrothermal systems, access that can only be provide by ocean drilling.

One possible drilling target is the PacManus hydrothermal site located 30-km off shore of New Britain. An extensive hydrothermal system developed in andesitic to dacitic rocks has been discovered, and the site has been proposed for ODP drilling (Fig. 4). If detailed site survey work shows that the deposits are sufficiently large, mature, and amenable to drilling with existing technology, this site may be suitable for addressing many of the questions regarding the formation of large arc-related volcanogenic massive sulfides deposits.

Mature drilling targets for addressing other styles of mineralization related to arcs, such as epithermal deposits related to the upper levels of porphyry Cu deposits, remain to be defined. Gold-rich seafloor hydrothermal systems, such as the one discovered off-shore of the world class Ladolam Au deposit are certainly intriguing possibilities, but more extensive site survey work is needed before drilling can proceed. However, scientific drilling in an area such as this would certainly generate intense interest in a large portion of the economic geology community that at present is not directly involved with ODP related studies.

Drilling targets for investigating the large sedimentary-exhalative type massive sulfide deposits have not been identified to date. Identifying a seafloor analog to these important systems would be a major discovery and could easily justify a high priority for drilling by ODP. Some questions regarding formation of these deposits can be addressed by drilling in the very large sulfide deposit developed in the Atlantis II Deep in the Red Sea, and this must be considered as one of the high priority sites for addressing metallogenesis. However, discovery of a large hydrothermal deposit in a continental margin setting typical of sedimentary-exhalative deposits remains an unfulfilled goal.

DRILLING STRATEGY

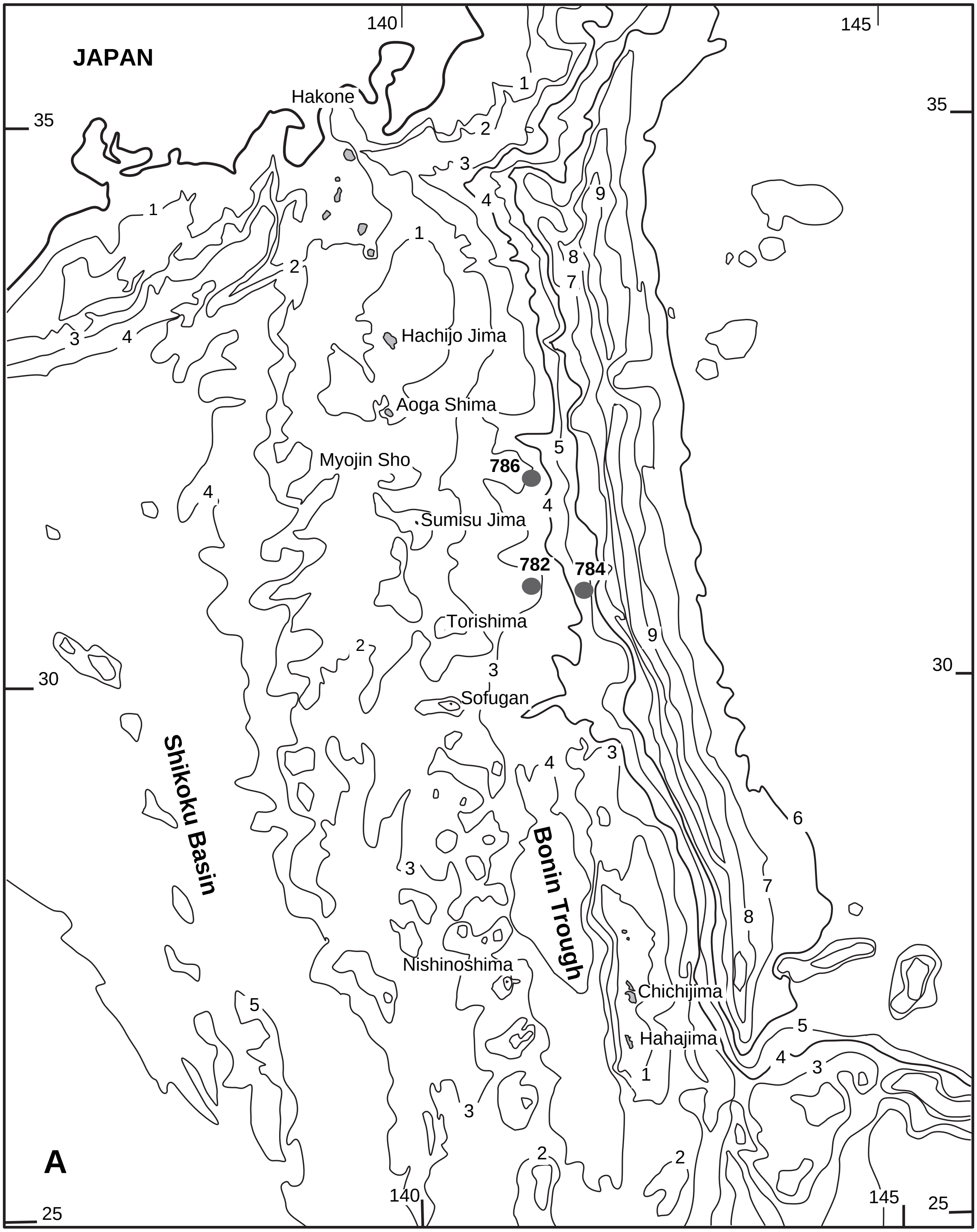
The drilling strategy for investigating arc-related hydrothermal systems will parallel that which was successfully applied in investigating the Middle Valley and TAG hydrothermal systems. We can conceptually divided hydrothermal systems in to three inter-related parts. The most difficult to investigate is the recharge portion of the system because the system is diffuse and geochemical changes are subtle, so properly targeting drill holes to investigate these processes is challenging. The high-temperature portion of the system that both drives fluid flow and controls the composition of hydrothermal fluids requires deep-drilling. Because active fluid flow and geochemical processes are difficult to investigate in deep, high-temperature borehole environments, the optimal strategy for investigating the reaction zone is to drill a large, mature hydrothermal system so that 1) there is a reasonable chance of intersecting the target of interest, and 2) there is an integrated record of water-rock interaction that can be addressed by examination of the recovered core. The hydrothermal upflow zone is the site of mineral deposition, both on and below the seafloor. Shallow subsurface fluid flow and mixing can have a large influence on the development of mineral deposits. Investigation of this portion of the system requires a higher density of drill holes and the ability to precisely site drill holes relative to seafloor targets such as active discharge sites. The complexities and spatial heterogeneity of these systems are best addressed by drilling technologies that have high core recoveries, but drilling in the porous and brecciated upper portions of immature hydrothermal systems has proven to be technologically challenging.

Massive sulfide deposits on-land are primarily investigated by slim line diamond core drilling. The major technological advancement that would improve our ability to investigate active hydrothermal systems would be successful development of a diamond-coring system for the drilling vessel. The improvement in core recovery and hole stability that are anticipated in sulfide drilling using this system would greatly enhance our ability to investigate the upper portions of these systems and should improve our ability to drill the deeper portions of hydrothermal systems. Drilling at both the Middle Valley and TAG hydrothermal sites have demonstrated that high temperatures in active hydrothermal systems have not posed major problems for drilling due to efficient cooling by circulating drilling fluids. However, the availability of high-temperature logging tools and cables, particularly if we switch to slim line drilling, remains as a significant limitation that should be addressed through technological development.

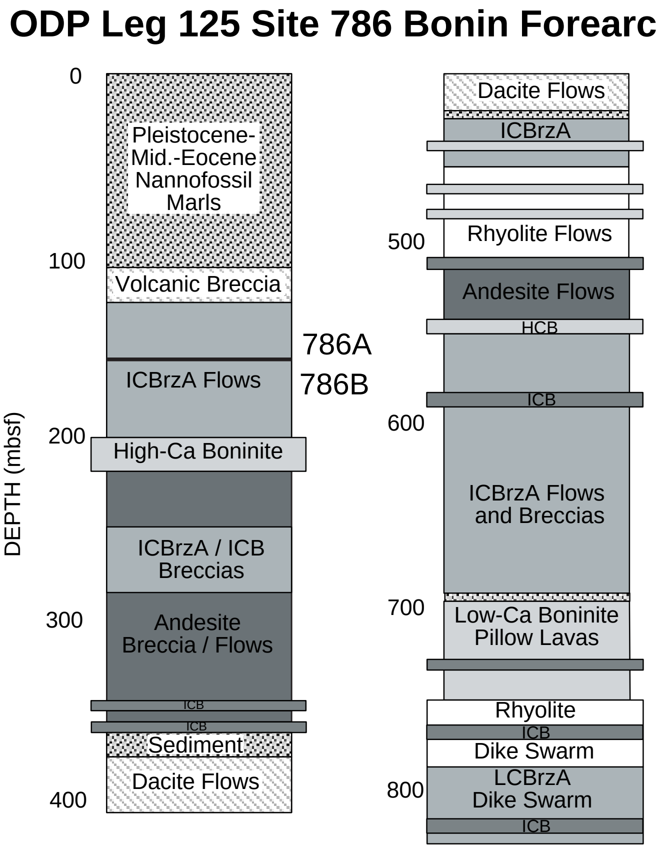
Coordination with other initiatives

The InterRidge Meso-scale Studies Working Group report *Back-Arc Basin Studies: A Workshop* (InterRidge, 1994) identified the study of the influence of subduction on ocean ridge processes in back-arc basins as one of their principal goals. They highlighted 3 areas of study in particular: (1) the geochemical influence of subduction on melt generation and hydrothermal activities, (2) the geophysical and tectonic effects of subduction on ridge segmentation and ridge evolution in back-arc setting, and (3) the influence of the biological and chemical fluxes from back-arc basins on the global environment. Such objectives are clearly of interest to the oceanic lithosphere community. The actual seagoing research program for this InterRidge initiative, which will be achieved by international, multi-country efforts, was being prepared, at the time of this workshop, and was planned to be completed be completed in September, 1996. The tentative program stressed seismic tomographic experiments using an OBS transect to get a detailed image of the upper mantle beneath the back-arc basin spreading system, intensive geophysical mapping by swath bathymetry along with other conventional geophysical mapping, and detailed rock sampling.

This working group is in sympathy with many of the objectives identified by the InterRidge working group on Back Arc Basins, and can foresee an important role for ocean drilling, relevant not only to the InterRidge community, but also to the oceanic lithosphere community. Not surprisingly, the research activities outlined by the InterRidge report are based largely on the results of ODP drilling in the western Pacific (e.g., Taylor and Natland, 1995). Furthermore, considerable survey efforts in the western Pacific are planned for the near future or already underway. Nevertheless, identifying a strategy for drilling in this environment is beyond the scope of the working group from this meeting. Clearly, a meeting that including individuals from all of the interested groups (e.g. oceanic lithosphere, margins, InterRidge) is needed to develop the scientific rationale for such a program in the near future.

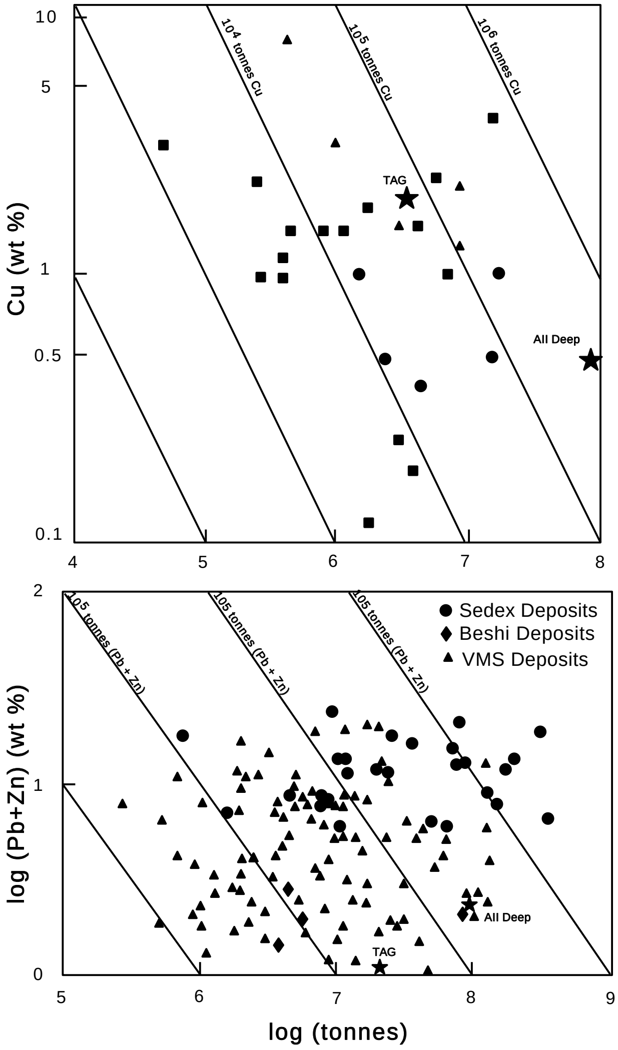


Section 4.5, Figure 1: Bathymetric map of the northern Philippine Sea showing the location of ODP Sites 782, 784 and 786.

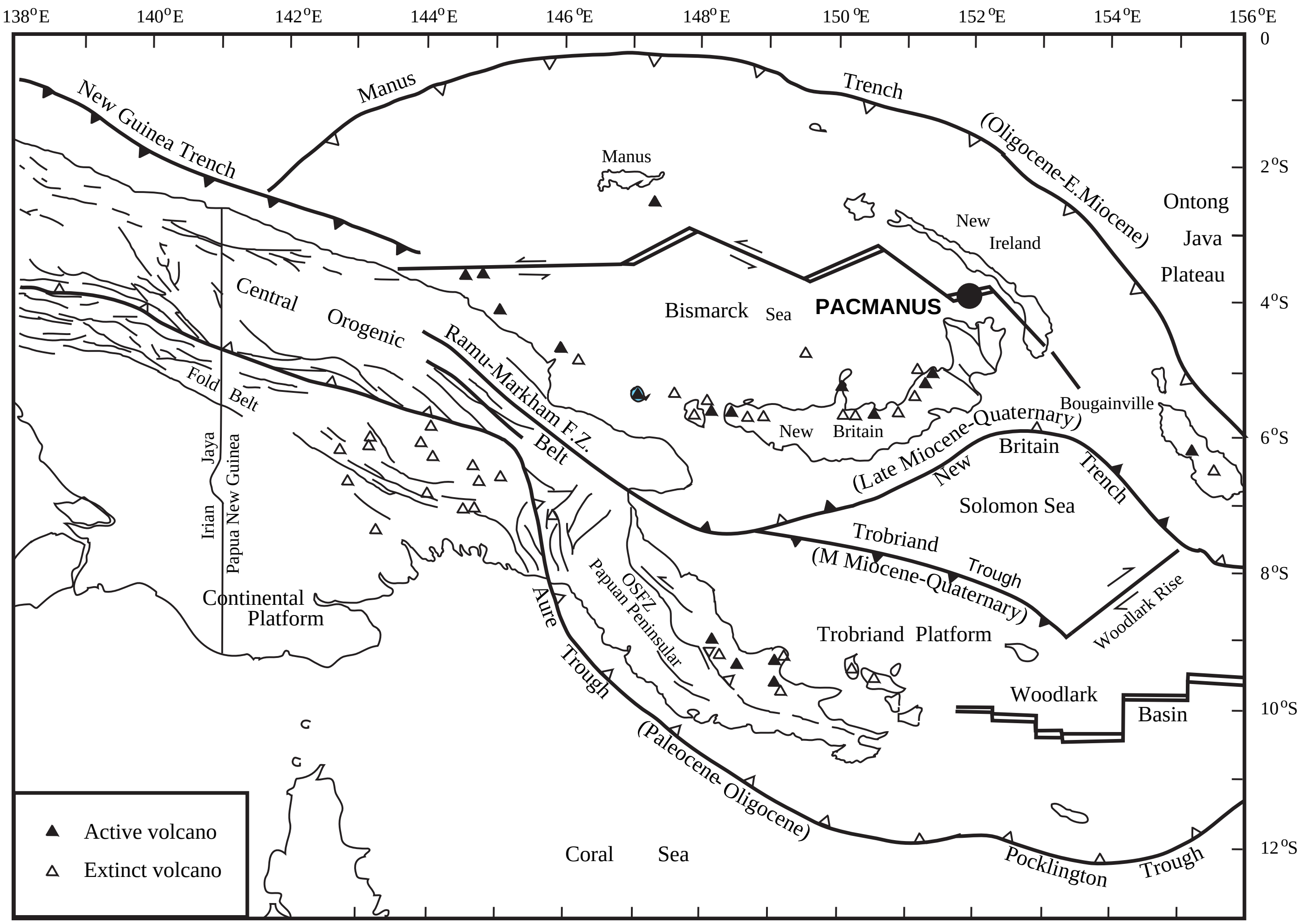


ODP Leg 125 Site 786 Bonin Forearc

Section 4.5, Figure 2: Stratigraphic column for Site 786 in the Bonin Fore-arc.



Section 4.5, Figure 3: A. Plot of Copper grade verses tonnage for ophiolite-hosted massive sulfide deposits in Cyprus (squares, circles show stockwork dominated deposits) and Oman (triangles). The estimated size of the TAG mound and stockwork on the Mid Atlantic Ridge and the Atlantis II Deep deposit in the Red Sea are shown for comparison (modified from Hannington et al., in press). B. Plot of combined Pb + Zn grades verses tonnage for sedimentary exhalative deposits (circles), Beshi-type (mixed volcanic-sedimentary environment; diamonds), and volcanic-hosted (triangles) massive sulfide deposits. Note that the sedimentary-exhalative deposits tend to have much higher total metal contents than volcanogenic massive sulfides deposits in general. Comparison with Figure A shows that ophiolite-hosted deposits typically plot at lower tonnage and lower Pb + Zn grades than most volcanogenic massive sulfides deposits, many of which formed in association with volcanic arc like tectonic settings. The approximate positions of the TAG deposit (which contains less than 1% Pb + Zn) and the Atlantis II Deep are shown for comparison. The tectonic and geochemical setting of the Atlantis II deep is most similar to volcanogenic massive sulfides deposits, but the depositional setting provides an analog for sedimentary-exhalative deposits.



After Cooper and Taylor (1987)

Section 4.5, Figure 4: Tectonic setting of the PACMANUS hydrothermal deposit in the Manus back-arc basin, Papua New Guinea.

5 - REFERENCES

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6 - MEETING AGENDA

The Ocean Lithosphere & Scientific Drilling into the 21st Century

SUNDAY, MAY 27: SEA CREST RESORT AND CONFERENCE CENTER

INTRODUCTION AND WELCOME

8:30 AM	Henry Dick and Catherine Mével

OVERVIEWS

8:45 AM	The Ocean Drilling Program, It's Present and Future, and its Relationship to International Earth Science Initiatives: Dr. Rob Kidd, Chair, JOIDES Planning Committee
9:00 AM	*The 4D architecture of the Oceanic Crust: Results of the InterRidge and Rises Planning Process* - Roger Searle
9:15 AM	*Oceanic Large Igneous Provinces and the Results of Planning the LIPs Initiative* - Mike Coffin
9:30 AM	Discussion - Catherine Mével

SYMPOSIUM ON THE COMPOSITION & STRUCTURE OF THE OCEAN LITHOSPHERE: PRESENT KNOWLEDGE & MAJOR GAPS

1. Volcanic Stratigraphy and Geochemical Evolution

10:00 AM	*Contrasts in Seafloor Morphology and Implications for Crustal Accretion along the Ocean Ridges* - Rob Pockalny
10:20 AM	*The Geochemical Perspective* - Rodey Batiza
10:40 AM	*The Internal Fabric of The Ocean Crust* - Sue Agar
11:00 AM	Discussion, Dave Christie
11:20 AM	*Seafloor & Sediment Hosted Sulphide Deposits* - Rob Zierenberg
11:40 AM	*Shallow Subseafloor systems* - Jeff Alt
12:10 AM	Physical properties of the shallow crust - borehole experiments - Keir Becker
12:30 PM	Discussion - Susan Humphris
1:00 PM	Buffet Lunch

2. The Lower Ocean Crust and Upper Mantle

2:00 PM	*Geodynamic Evolution of the Lithosphere* - Jian Lin
2:20 PM	*Melt Transport and Crustal Accretion in the Lower Crust* - Jim Natland
2:40 PM	*Generation, Accumulation and Transport of Melt in the Shallow Mantle* - Peter Kelemen
3:00 PM	Discussion - Don Elthon
3:30 PM	Break
3:45 PM	*Tectonic Evolution of the Lower Crust & Shallow Mantle* - Mathilde Cannat
4:05 PM	*Hydrothermal Circulation and Alteration in the Lower Crust & Mantle* - Catherine Mével
4:25 PM	*Physical Properties of the Lower Crust and Mantle* - Jay Miller
4:45 PM	Discussion - Deborah Kelley
5:15 PM	Back Arcs, Fore-Arcs and Ocean Crust - Brian Taylor
5:35 PM	Discussion - Richard Arculus
5:55 PM	Break for Dinner
7:30 PM - 10 PM	Ice Breaker and Poster Session (Contributed Papers)
9:00 PM	Steering Committee Meeting (to discuss working groups)

MONDAY, MAY 27: SEA CREST RESORT AND CONFERENCE CENTER

8:00 AM	continental breakfast
8:30 AM	*Evaluating Ocean Crust Biomass* - John Delaney
8:50 AM	Discussion - Jean Whelan

3. Oceanic Large Igneous Provinces

9:10 AM	Overview - Mike Coffin
9:50 AM	Discussion - Will Sager
10:10 AM	Break

SYMPOSIUM ON CHOOSING TARGETS AND DRILLING THEM

The Technology of Hard Rock Drilling in the Oceans:

10:25 AM	*Present and Likely Technology or 1998-2003.* Tim Francis ODP-TAMU
10:45 AM	*Future and Likely Technology for 2003 and Beyond - Deep Ocean Riser Drilling*. Hajima Kinoshita JAMSTEC
11:05 PM	Discussion - Rob Kidd

Holes - Not Just a Place to Store Water

11:25 PM	*Current Approaches to Logging and Down-Hole Experimentation* - Dr. David Goldberg, Lamont Doherty Geological Observatory
11:55 PM	*Drilling Deeper Holes with Current Technology*. Phillipe Pezard
12:15 PM	*Towards Deeper Holes - a Strategy for the Immediate Future* - Jim Natland
12:35 PM	Discussion - Jamie Austin
1:00 PM	Buffet Lunch - Steering Committee Meeting

DOWN TO BRASS TACKS: WORKSHOP ON FUTURE DRILLING

2:00 PM	*Between a Rock and a Hard Place - The Realities of Ocean Drilling - Practical Limitations, Politics, and Strategies for Drilling the Ocean Lithosphere 1998-2003*- Roger Larson
2:15 PM	Discussion - Catherine Mével
2:30 PM	Setting Priorities, Identifying Proposals and Working Groups - Bob Detrick
3:00 PM	Working Group Meetings
4:30 PM	Initial Working Group Reports
5:00 PM - 6:00 PM	Steering Committee Meeting
6:30 PM	USSAC Hosted Dinner - Clark Laboratory, Woods Hole Oceanographic Institution

MAY 28: SEA CREST RESORT AND CONFERENCE CENTER

8:00 AM	Continental Breakfast
8:30 AM	Working Group Meetings
11:00 AM	Second Report of Working Groups
12:00 Noon	Buffet Lunch
1:00 PM	Working Group Meetings and Draft Outline & Proposal Writing
3:00 - 3:15 PM	Break
3:15 PM	Final Plenary Session

MAY 29: CLARK LABORATORY, WOODS HOLE OCEANOGRAPHIC INSTITUTION

8:30 AM	Steering Committee and volunteers draft final report
12:00 Noon	Buffet Lunch
1:00 PM	writing
5:00 PM	end of meeting

7- ABSTRACTS OF POSTERS PRESENTED AT THE MEETING

Full text versions of the abstracts presented at the meeting are in: *The Oceanic Lithosphere & Scientific Drilling into the 21st Century*, program and abstracts, published by the InterRidge Office, Dept. of Geological Sciences, University of Durham, South Road, Durham, DH1 3LE, United Kingdom.

1. Agar, S.M., Lloyd, G.E.: *Deformation of Fe-Ti Oxides in gabbroic shear zones from the Mid-Atlantic Ridge at Kane area.*
2. Bueckner, C.J., Delius, H., Wohlenberg, J. and ODP Leg 163 Shipboard Scientific Party: *Basaltic lava flows in the northern Atlantic: Magnetic properties in relation to structural features.*
3. Casey, J.F., *Major and trace element geochemistry of Leg 153 abyssal peridotites and mafic plutonic rock from the Mid-Atlantic Ridge at Kane region*
4. Castillo, P.R. and Janney, P.E.: *The geochemical evolution of the Pacific upper mantle and the isotopic diversity of modern mid-ocean ridge basalts.*
5. Christie, D.M., West, B.P., Sempéré, J.-C., and Pyle, D.G.: *Mantle migration and the history of the Australian-Antarctic discordance: A progress report.*
6. Constantin, M.: *Residual harzburgites, pyroxenite veins and melt impregnated peridotites from the Terevaka and Garret Transform faults along the fast-spreading southern East Pacific Rise.*
7. Dilek, Y., Kempton, P.D., and Thy, P.: *Deformation and hydrothermal alteration history of progressively cooled gabbros in the Mid-Atlantic Ridge at Kane area.*
8. Dmitriev, L.V., Danyushevsky, L.V., Plecheva, A.A., and Melson, W.G.: *Pressure, temperature and water content regime of normal and enriched mid-ocean ridge basalt fractionation along Mid-Atlantic Ridge axial zone.*
9. Duncan, R., Donnelly, T.W., Mauffret, A., Driscoll, N. and Diebold, J.: *ODP drilling targets on the Caribbean Plateau.*
10. Frey, F.A., Weis, D., Coffin, M.F., and Schaming, M.: *Kerguelen Plateau: the case for an ocean drilling program.*
11. Grevemeyer, I. and Weigel, W.: *Upper crustal structure as a function of plate age: The status after twenty years.*
12. Hooft, E.E.E., Schouten, H. and Detrick, R.S.: *Constraining crustal emplacement processes from the variation in seismic layer 2a thickness at the East Pacific Rise.*
13. Humphris, S.E., Herzig, P.M., Miller, D.J., Alt, J.C., Becker, K., Brown, D., Brügmann, G.E., Chiba, H. Fouquet, Y., Gemmell, J.B., Guerin, G., Hannington, M.D., Holm, N.G., Honnorez, J.J., Iturrino, G.J., Knott, R., Ludwig, R., Nakamura, K., Petersen, S., Reysenbach, A.-L., Rona, P.A., Smith, S., Sturz, A.A., Tivey, M.K. and Zhao, X.: *The subsurface nature of the TAG hydrothermal mound: preliminary results of ODP Leg 158.*
14. to, G. and Clift, P.: *Evidence for age-progressive accretion of the Manihiki and Ontong Java Plateaus from their vertical tectonic histories.*
15. Johnson, K.T.M., Scheirer, D., Forsyth, D., Graham, D., and the Boomerang Expedition, Leg 6 Scientific Party: *Interactions between the Southeast Indian Ridge and the St. Paul/Amsterdam Islands Hot spot: Preliminary results.*
16. Jonasson, B. and Pollard, G.: *Hard rock drilling tools options.*
17. Kelemen, P.B., Koga, K., Aharonov, E., Whitehead, J.A., Shimizu, N. and Hirth, J.G.: *Gabbroic sills in the crust/mantle transition in the Oman Ophiolite: Implications for the genesis of the oceanic lower crust.*
18. Kelley, D.S. and Früh-Green, G.L.: *A new reservoir for methane in mid-ocean ridge hydrothermal systems.*
19. Kroenke, L.W., Mahoney, J.J., Saunders, A.D., Wessel, P. and Bercovici, D.A.: *Assessing the origins age and post-emplacement history of the Ontong Java Plateau through basement drilling.*
20. Kurnosov, V.B. and Murdmaa, I.O.: *Hydrothermal and cold-water circulation within the intraplate seamounts: effects on rock alteration.*
21. Manning, C.E. and Weston, P.E.: *Onset of metamorphism in East Pacific Rise Lower Crust, Hess Deep: Temperature, time and fluid composition.*
22. McInnes, B.I.A.: *The composition and structure of oceanic lithosphere at a convergent plate boundary.*
23. Mottl, M.J.: *Hydrothermal circulation through mid-ocean ridge flanks: Insights from ocean drilling.*
24. Nazarova, K.A., Wasilewski, P.J. and Dick H.J.B.: *Magnetic petrology of the oceanic serpentinites.*
25. Pringle, M.S., Duncan, R.A., Mitchell, C. and Wijbrans, J.: *A* ^{40}*Ar/*^{39}*Ar geochronology of (altered) volcanic rocks: Comparison of furnace- and laser-heating techniques.*

26. Rihm, R. and Henke, C.H.: *Early tectonic controls on Red Sea rifting, opening and segmentation.*
27. Rona, P.A., Cronan, D.S., Hannington, M.D., Herzig, P.M., Mills, R. Scott, S.D. and Smith S.E.: *TAG II: Evolution of a volcanic-hosted hydrothermal system on a slow-spreading ocean ridge.*
28. Sager, W.W., Klaus, A., Mahoney, J.J., Tatsumi, Y., Nakanishi, M., Sliter, W.V., Brown, G.R. and Khankishieva, L.M.: *Testing hypotheses of giant large igneous province formation at Shatsky Rise.*
29. Schouten, H., Hooft, E.: *Upper and lower pillow lava structure from drill cores in oceanic crust and the Troodos Ophiolite.*
30. Searle, R.C., Mitchell, N.C., Escartin, J., Slootweg, A.P., Russel, S. Cowie, P.A., Allerton, S., MacLeod, C.J., Tanaka, T., Flewellen, C. and Rouse, I.: *High-resolution TOBI study of the Broken Spur segment, Mid-Atlantic Ridge, 29°N.*
31. Silantyev, S.A., Dmitriev, L.V., Casey, J.F., Dick, H.J.B., Cannat, M., Bougault, H., Sobolev, A.A. and Bazylev, B.A.: *Anew perspective for offset drilling within the rift valley of the Mid-Atlantic Ridge in the 15°20'N region: The first data on isotope composition of Sr, Nd and Pb in Co-existing basalts, gabbro and residual peridotites as a geochemical indicator of their genetic conformity.*
32. Smith, D.K., Cann, J.R., Blackman, D.K. and the cruise participants of Charles Darwin Leg 100: *Detailed volcanic morphology near 29.5°N at the Mid-Atlantic Ridge based on TOBI bathymetry and side-scan sonar: first results.*
33. Stephen, R.A., Butler, R., Chave, A., de Moustier, C.P., Hildebrand, J.A., Nagihara, S. and Von Herzen, R.P.: *Drilling at the* H_2O *long term observatory.*
34. Stephen, R.A., Suyehiro, K., Montagner, J.-P., Dziewonski, A. and Romanowicz, B.: *Lithospheric drilling in support of the Ocean Seismic Network.*
35. Tappin, D.R., Kempton, P.D., MacLeod, C.J. and Bloomer, S.H.: *Ocean drilling in the Tonga Fore-arc: Subduction geodynamics, arc evolution and deformation processes at non-accretionary convergent margins.*
36. Teagle, D.A.H., Alt, J.C. and Halliday, A.N.: *Tracing the chemical evolution of hydrothermal fluids during recharge as recorded by anhydrote from DSDP/ODP Hole 504B.*
37. Tucholke, B.E., Lin, J., Kleinrock, M.C.: *Off-axis structure of spreading segments on the Mid-Atlantic Ridge at 25.4 to 27.2°N.*
38. Vanko, D.A.: *Does Hole 504B sample the "hydrothermal reaction zone?"*
39. Zolotarev, B.P. and Artamonov, A.V.: *Geological structure and evolution of transform faults.*

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