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Melting, Magma, Fluids and Life

Challenges for the next generation of scientific ocean drilling into the oceanic lithosphere.

Workshop Report

National Oceanography Centre, Southampton
University of Southampton, UK

27th to 29th July, 2009

Conveners:
Damon Teagle, Benoit Ildefonse, Donna Blackman, Katrina Edwards, Wolfgang Bach, Natsue Abe, Rosalind Coggon, and Henry Dick.

UNIVERSITY OF Southampton

National Oceanography Centre, Southampton
UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

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Damon Teagle (host)[1], Natsue Abe[2] , Wolfgang Bach[3], Donna Blackman[4], Rosalind Coggon[5], Henry Dick[6], Katrina Edwards[7], Benoit Ildefonse[8]

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National Oceanographic Center, Southampton, 27-29 July 2009

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Overview

From its formation at mid-ocean ridges, to its recycling in subduction zones, the oceanic lithosphere serves as the major "process zone" for heat and material exchanges between Earth's deep interior and the surface. Only within this thermally and hydrologically dynamic region is there direct interplay between mantle, crust, and ocean. The natural variability in thermal conditions associated with differences in accretionary magma supply and tectonic history fosters fascinating differences in the nature of hydro-bio-geochemical interplay within the young (≲1 m.y.) lithosphere. Deep sea ecosystems thrive on the seafloor of oceanic spreading centers in zones with the highest thermal or chemical gradients, but the nature and extent of microbial life on/within the lower thermal and chemical gradients of aging ocean lithosphere (1-100 m.y.) remain unknown. Although the dominant fluid-rock reactions that occur during hydrothermal alteration of the ocean crust are well established, the magnitude of chemical exchange between the ocean lithosphere and the oceans remains poorly quantified principally because of our sparse and unrepresentative sampling of the ocean crust. Over the last decade or so, a major change in our understanding of the ocean crust has occurred with the discovery that crust formed at slow and ultraslow spreading ridges is extremely diverse, ranging from large areas of the oceans floored by altered mantle rock, to regions with a thick layered crust. Although ocean crust formation in the Pacific occurs at a vastly greater rate, the crust at slow and ultraslow spreading ridges will exchange with the oceans by very different reactions and is likely to play an important, hitherto unaccounted for, role in controlling ocean chemistry. This provides a new impetus for a major societal priority, which seeks to understand global chemical cycling and its impacts on climate change. To understand the major drivers of climate change it is crucial to quantify the sources, sinks, and pathways of heat and chemical transfer between the oceans and solid Earth. Only with these critical benchmarks can we confidently compare exchange fluxes with the ocean lithosphere with those from other components of the Earth system (e.g., rivers) that also affect ocean chemistry.

A key outcome of this workshop was the formulation of integrative scientific questions and implementation approaches that will elucidate the role of ocean lithosphere processes within the broader Earth System. The focus is mostly on the igneous/metamorphic basement. There are three main aspects, each comprising geological, hydrological, chemical, and biological processes that are closely interdependent.

1) *Understanding the* ***initial conditions****, in particular the lithological architecture and resulting physical/rheological and chemical/ mineralogical properties and ramifications for exchange with the oceans and subseafloor life. Reaching this goal requires (a)* ***full section characterization*** *of an intact section of ocean crust continued a significant distance into the uppermost mantle, and (b) detailed understanding of* ***active processes within the axial zone****, such as magma plumbing and distributions, seawater circulation, magma-fluid-rock interaction, and microbial colonization.*

2) *Understanding* ***lithospheric heterogeneity*** *in slow- and ultraslow spread crust and the development of detachment faults, including the role of serpentine and talc. The production of hydrogen and methane during serpentinization provides a* ***direct link between mantle and microbes****, as these compounds support microbial life at and below the seafloor. Such environments may mimic conditions on the early Earth. The abundance of serpentine and its high water content makes it an important reservoir of water and assessing the role of these "****serpentine seas****" in the planetary water cycle is a high priority.*

3) *Following the* ***maturation process*** *of lithosphere in hydrologically and biogeochemically active systems on the ridge flanks and investigating the hydrological-geochemical-microbiological feedbacks in aging seafloor. Better quantification of* ***seawater-ocean lithosphere chemical, fluid and thermal exchange fluxes*** *is essential to more confidently define many major geochemical cycles (e.g., CO_2, Mg, K, Li, B, $^{87}Sr/^{86}Sr$). Of crucial importance will be furthering our understanding of spatial and temporal microbial habitat development and fluid-microbe-mineral interactions and their* ***controls on exchange rates between the crust and the oceans****.*

The first section describes the scope of workshop discussions. Points of consensus developed within each Breakout Group are detailed in the subsequent "Outcomes" section. This report presents a compilation of ideas and key hypotheses to be tested that were discussed and highlighted during the workshop. The societal relevance of the envisioned research ranges from mineral and biomedicine resource potential, to influences of lithosphere architecture on the level of hazard present within subduction zones, assessment of carbon uptake rates within seafloor mantle exposures or on the vast basaltic ridge flanks, and engendering public excitement about frontier science and enhanced educational benefit thereof.

Introduction

With the imminent development of new research plan for scientific ocean drilling, members of the InterRIDGE Deep Earth Sampling Working Group decided that it would be timely for the extended ocean lithosphere scientific community meet, to review achievements and identify future experiments that will refine our knowledge of the mid-ocean ridge processes and the myriad chemical and biological exchanges between the ocean crust and the wider Earth system.

Major financial support for the meeting was raised from InterRIDGE, NOCS, UK-IODP, COL-USSSP as well as other national agencies that support scientific ocean drilling. An international group of ~75 scientists gathered at the National Oceanography Centre, Southampton for three days of state-of-the-art science lectures, and working group and plenary discussions (27 to 29th July, 2009). The workshop included an evening guest lecture by Peter Kelemen about utilizing hydrothermal reactions with peridotite for carbon capture and storage. The list of participants, the abstracts of lectures, the abstracts of posters and white papers, and copies of the lecture presentation files are provided in the appendices of this report.

The workshop had four principal aims:

(1) to review and assess our current understanding of ocean lithospheric processes from mantle melting to crustal magmatism, ridge axis and flank hydrothermal exchange, tectonic variability, global biogeochemical cycles, and novel ecosystems and environments;

(2) to highlight the successes of past drilling of the oceanic crust and identify key knowledge and sampling gaps;

(3) to engage the broad community of scientists with interests in ocean crustal processes and the vast ocean basement environments in fostering future integrated research programs;

(4) To identify key scientific questions, objectives, challenges, and technical requirements for future scientific drilling of the oceanic lithosphere to better inform discussions at the September 2009 INVEST meeting.

The priority of this workshop was to develop future goals for understanding the ocean lithosphere and related geochemical and biological interactions. The exchange and exploration of new ideas that will spur future progress were a priority. Our aim was not to design future drilling proposals but to build community momentum along the new and established research avenues that will shape the future priorities of scientific ocean drilling and guide innovative experiments by the broader earth science community.

Scope of Workshop Discussions

Keynote lectures - Plenary Discussion #1

The Day 1 keynote lectures (see workshop agenda, appendix A) highlighted several points, some reflecting long-term goals for basement ocean drilling that still have not been addressed, and many arising from findings of the past decade (see abstracts and presentations in appendices C and D). To incite discussion, aspects of these keynote lectures were highlights by "off the cuff" summaries by Mike Cheadle and Laurence Coogan.

Although insights on formation of intrusive crust at detachment-dominated, slow-spread lithosphere have been obtained (ODP Legs 118, 153, 176, 209, and IODP Site 1309; e.g., Dick et al., 2000; Blackman et al., 2006; Kelemen et al., 2007; Ildefonse et al., 2007) the thermal regime and melt supply/delivery in these settings differs significantly from those of the axial zone in fast-spreading lithosphere. There remains a near complete lack of direct evidence regarding the accretion occurring beneath the volcanic layer throughout the Pacific. This matters because the formation of ocean crust at fast spreading ocean ridges is the dominant process that has re-surfaced ~60% of our planet in the past <200 M.yrs. The latent and specific heat from cooling and crystallizing magma is the principal driving force for hydrothermal circulation with the energy available a function of the volume, distribution, and timing of magma intrusions. The compositions of fluids venting into the ocean at high temperature black-smokers and other types of vents are controlled by the physiochemical conditions and the extents of fluid-rock reactions within the crust. The rate of cooling of magma controls and is in turn controlled by the extents of fracturing, and the resulting permeability, the distribution of high and low temperature hydrothermal circulation, and rates of fluid-rock exchange. Microbial populations seek out high thermal/chemical gradients, hence temporal variation in the location/properties of these zones is expected to determine the diversity of the ecosystem. If microbial exchange is sufficient there may be feedbacks whereby near-seafloor porosity becomes sealed causing the deeper crust to cool at a slower rate than during periods of vigorous circulation. Recent numerical models and ophiolite data (e.g., Maclennan, 2005; Bosch et al., 2004) require that seawater circulation extends to depths of several km close to the ridge axis, and hence directly control accretionary processes in the lower crust. Unfortunately the petrologic and structural test of this scenario in an intact section of ocean crust remains to be conducted. An important recent advance comes from the recognition that the sheeted dike section at all fast-spread systems studied (ODP Holes 504B, 1256D, seafloor samples from Hess and Pito Deep tectonic windows) provide consistent estimates of axial, high temperature fluid fluxes (e.g., Teagle et al., 2003, Gillis et al., 2005; Barker et al., 2008; Harris et al., 2008). These estimates are all much lower than hydrothermal fluxes estimated from global seawater budgets, hydrothermal vent observations (e.g., Elderfield and Schultz, 1995) or studies of ophiolites (Bickle and Teagle, 1992), but their consistence with thermal calculations gives confidence in their validity. This sets the stage for estimates of chemical flux between this zone and the oceans and the impact of axial hydrothermal alteration of global chemical cycles (e.g., Davis et al., 2004; Vance et al., 2009). Unfortunately, there is no comparable information for the more variable upper crust in slow-spread systems where drilling has yet to penetrate significantly into sheeted dikes. It is presently difficult to confidently extrapolate the fast spreading rate flux estimates to the global scale.

For decades it has been assumed that the compositions of mid-ocean ridge basalts (MORB) erupted on to the ocean floor could be interpreted as a direct result of mantle melting. However, recent results (Rubin and Sinton, 2007; Lissenberg and Dick, 2008; Suhr et al., 2008; Godard et al., 2009; Drouin et al., 2009) indicate that significant reactions occur between melts and lower crustal/mantle cumulates. The extent to which melt-rock interactions bias our current understanding of mantle melting processes, cannot be assessed without studying genetically related mantle, lower crustal, and extrusive sections. Although regions with extensive exposures of mantle on the seafloor offer some insight into mantle-melt relationships, it is most likely that the thermal regime (i.e., melting volume/history) in these areas is distinct from that of at least half of slow-spread and virtually all faster-spread lithosphere. Recent Os dating results on abyssal peridotite samples show that the major mantle depletion event(s?) in some areas occurred in the ancient past (Harvey et al., 2006; Liu et al., 2008). This requires renewed evaluation of melt-residue relationships and, potentially, a paradigm-shift in our understanding of fundamental Earth differentiation processes.

The discontinuity in seismic velocity that represents the transition from mafic to ultramafic compositions is often inferred to mark the base of the crust. The global similarity in depth (~6-7 km) of this Mohorovicic discontinuity (Moho) in the oceans underlies the premise that magma production rates scale with spreading rate to produce an essentially constant thickness of mafic crust. Many mantle flow and melting calculations use this premise to adjust poorly constrained physical parameters (e.g., temperature, viscosity) that impact predictions. However, whether some of the ultramafic rocks are igneous cumulates as opposed to residual mantle peridotites remains unknown. The transition from mafic to ultramafic rocks is irregular in some ophiolites. In other regions petrological and geophysical evidence suggest that the Moho is an alteration/serpentinization boundary. These may simply be competing hypotheses, or it may be that the Moho in different regions may be a different kind of discontinuity. These hypotheses can only be tested by direct sampling, and this has long been a strong motivator for scientific ocean drilling.

Not only would Moho penetration in different settings answer these questions, a suite of hypotheses about the cause of uppermost mantle anisotropy, seismic reflectivity, the relative motions of the crust and the underlying mantle, and magneto-telluric signatures could also be addressed in-situ for the first time. Extending these locally ground-truthed insights to the broader region will guide models of along-strike variability in structure and causes/consequences of ridge segmentation.

Hydrothermal chemical exchange between the crust and oceans is a fundamental component of global geochemical cycles, affecting the composition of the crust, the oceans and, through subduction, the mantle and arc magmas. Seawater chemistry reflects the balance between riverine, hydrothermal, biological and sedimentary fluxes to and from the oceans. Since the magnitudes of these fluxes depend on key global geologic processes including plate tectonics, climatic conditions, and biological processes, temporal variations in seawater chemistry can provide insights into fundamental Earth processes of clear societal relevance. However, reconstructing reliable records of past seawater chemistry and deconvolving the processes responsible for temporal variations in such records remain major challenges.

Although recent studies of slow spreading ocean ridges have recognised significant departures from the standard Penrose stratigraphy of the ocean crust, the oceanic lithosphere reservoir is young (<200 Ma), and *relatively* monotonous in composition compared to the continents, which are old, highly heterogeneous and isotopically radiogenic. This gives some confidence in the proposition that if we can quantify the hydrothermal exchanges that occur in the ocean crust, this will provide a rigorous benchmark against which variations in other major processes contributing to global chemical cycles can be compared. Recent studies have demonstrated that altered sections of oceanic basement can be used both to reconstruct past seawater chemistry (e.g., Teagle et al., 2007; Coogan, 2009) and to investigate the processes responsible for changing ocean chemistry (e.g., Davis et al., 2003, Vance et al., 2009). Improved understanding of the controls (e.g., spreading rate, crustal age, and sedimentation history) on the nature and extent of hydrothermal alteration, combined with estimates of past crustal production, could be used to predict past hydrothermal contributions to the oceans and estimate the riverine fluxes required to balance past variations in ocean chemistry.

Previous ocean basement drilling efforts have predominantly been made in young (<20 Ma) and ancient (> 110 Ma) crust. No hole penetrates deeper than 50 m in 45-80 Ma basement, the interval in which the crust is thought to be "sealed" to circulating fluids. Drilling of intermediate age upper crust, preferably along a crustal flow line, would provide essential information on how the crust ages as well as better age resolution for investigations of past seawater chemistry based on crustal alteration.

Heterogenous "crust" makes up at least 25% of slow-spread crust and seafloor exposures suggest that about ¾ of such regions is ultramafic rock (e.g., Cannat et al., 1995, 2006; Smith et al., 2008; Escartin et al., 2008b). When heterogeneous crust undergoes hydrothermal alteration it behaves dramatically different from basaltic crust. There is a distinct impact on rheology by making talc- and serpentine-bearing "weak" lithologies (e.g., Escartin et al., 2008a). The fluid-rock equilibria that control vent fluid chemistries in ultra-mafic hosted environments are very different from those in basalt-hosted systems. These differences have significant consequences for hydrothermal and rock-harboring microbial communities. The influence of the alteration of heterogeneous crust on hydrothermal exchange budgets remains poorly quantified (Vils et al., 2008, 2009) but it is very likely to be significant for elements such as B, Li, H, and C, and their isotopes. Serpentinization influences the character and behavior of subducting plates and is a crucial component in the planetary water cycle; it is likely a key "Earth reaction" and a potential setting in which early life on Earth developed. Also, in these regions, gabbroic rocks can be directly subjected to low temperature seawater alteration, and these reactions could contribute significantly to global chemical budgets (e.g., Bach et al., 2001; Alt and Bach, 2006). Importantly though, we could make major progress in quantifying hydrothermal exchange fluxes in both intact and heterogeneous ocean crust with a tangible number of shallow to moderate (~100 to 500 m) depth drill holes.

Just as for the ramifications of serpentinization for life (and the potential feedbacks), little is known about the role of microorganisms in the alteration of oceanic basalt. Although there is mounting molecular evidence for microbial activity within ocean crust (e.g., Santelli et al., 2008), we are as yet unable to quantify the impact of microbial colonization on ocean-crust exchange budgets. Nonetheless, microbial activity within the basaltic crust has pronounced feedbacks on the rates and pathways of chemical transformations. From an evolutionary perspective, these interactions may have profound geobiological implications over Earth history.

INVEST and a New Ocean Drilling program

Steering committee members for INVEST explained the remit for discussions that will be aimed at elucidating the science that a new drilling program would address. The prominence of societal relevance, integrative research, and transformative results that future drilling would have were emphasized.

Breakout Sessions #1– Key aspects of the evolution of ocean lithosphere

The audience was split in two groups for these first breakout sessions.

Group 1A discussed the formation of lower crust and the heat/mass transfer between the mantle and the upper crust that is determined by the processes therein. The fundamental role that hydrothermal circulation plays, both on and off-axis, in controlling cooling rates and chemical exchange was emphasized.

Newly recognized contrasting styles of crustal architecture at slow and ultraslow ridges range from large areas where the crust is composed of serpentinized mantle, areas where it is composed of gabbro intrusions in serpentinized mantle with scattered lavas, to areas with a more conventional layer-cake crust of gabbro dikes and basalt, have major implications for the extent, diversity, and character of hydrothermal exchanges between the crust and the ocean. Opportunities to document serpentinization processes are uniquely available in detachment-dominated lithosphere. Given the spatial variability in architecture in at least some settings, contextual studies (geophysics, seafloor geology, hydrology) were recognized to be crucial to most ocean lithosphere projects within which drilling occurs. The fundamental role of the ocean lithosphere within the global Earth system, via hydrologic transfers and determining styles of geologic activity during subduction were highlighted.

Group 1B also discussed geochemical cycles and alteration of the aging lithosphere, pointing out the likely role of microbes in these processes. There was strong interest in how the transition from open-system hydrothermal flow to closed-system might influence microbial populations. The possible role of seamounts as possible conduits for heat and fluid on sediment covered ridge flanks was introduced. Similar to Group 1A, this group considered the diversity of lithospheric structure and how magma supply and deformation come into play. Again, the need for local ground truthing through drilling to guide regional geophysical studies was underscored, both in a given area and to address along-strike variation in accretion processes and their temporal history. If a full penetration through the crust and into the upper mantle is achieved in intact crust formed a fast spreading rate, this would capture a hitherto unknown view of the (paleo-) asthenosphere since the base of the crust is the base of the lithosphere in this thermal regime. Dynamic information relating to coupling between plate and large-scale mantle flow could be addressed together with long standing questions regarding mantle melting and the accretion of the lower ocean crust. Finally, this group emphasized processes occurring at active ridge crests. Whilst recognizing the technological challenges, the importance of observations of hydrothermal processes and mineralization, and the leverage that integration with observatories may provide were noted.

Plenary Discussion #2

Based on the interests brought out during the first breakout session several potential working group topics were proposed. Some additions and regrouping took place after a convener's initial listing and participants settled on four topics, which are listed under Breakout Sessions #2.

Day 2 lectures – Recent Technological Advances

New and exciting progress that can lead to deep penetration drilling in deep water (4000-4500 m) was reported. Recent technological advances include casing design, drill string materials and proven drilling capability at moderately high temperature (>250°C). Technologies for riser stabilization in high currents have been tested. Emerging riserless mud recovery systems with seafloor-based operation have reached encouraging milestones (operational in shallow-waters and design completion for deep-water system). Feasibility of the use of this type of system on existing scientific ocean drilling platforms has been assessed (Myers, 2008).

As important as the technological capabilities is the strength of the commitment of the scientific community to achieving deep penetration, and deep water drilling. A statement of the Japanese government's intent to have *Chikyu* drill a complete crustal section down into the mantle was clearly voiced, more strongly than in past public meetings. While recognizing the need for such a project to rise equitably within the science planning process to high priority, the long lead-time for a successful 'Mohole' requires that preparatory work starts as soon as possible. JAMSTEC has already started pursuing technological aspects (see above) as well as sponsoring collaborative geophysical surveys in one of a few envisioned prospective sites close to Hawaii. A potential concern at this site is the possible effect of the Hawaiian Arch volcanism, and this needs to be assessed explicitly. The region around Site 1256 and an area in the eastern Pacific off Mexico are other recognized prospective sites. Ideas were solicited for other possible sites that meet the water depth/lithospheric age (temperature) criteria and a majority of the long-term Mohole scientific objectives (see Mission Moho workshop report; www.iodp.org/mission-moho-workshop). Because of the relatively young age of Site 1256 (~15 Ma), and the expected relatively high temperatures at Moho depth, the need for dedicated modeling of the feasibility of drilling at such high temperatures was strongly expressed.

This session also highlighted the importance of developing techniques to determine the orientation of recovered cores in the geographical reference frame. In the absence of techniques that allow the acquisition of the full orientation during drilling, post-cruise techniques combining paleomagnetism and borehole imaging data represent an effective, albeit time consuming, alternative (Morris et al., 2008). Drilling lavas and dikes from the ocean crust is commonly fraught by low (<30%) and unrepresentative rates of core recovery. This leads to minimum estimates of the abundance of fragile and highly altered rock types (e.g., breccias) with the subsequent under-representation of these horizons in estimates of chemical exchange or quantifications of the sub-seafloor biosphere. Great value can be added to the core recovered by multiple traverses of the borehole with wireline imaging tools (e.g., FMS, UBI) to better constrain the lithologic proportions of the basement (e.g., Tominaga et al., 2009).

Analytical capabilities and major hypotheses to be tested have advanced significantly since the acquisition of several classic basement cores during DSDP, ODP and IODP (e.g., Sites 417/418; Hole 504B). Several times during the workshop it was pointed out that significant progress on key questions regarding the Earth system could be made through the application of newly developed techniques and a modern-re-investigation of the important ocean floor core archive preserved by the drilling program.

Scientific ocean drilling can contribute very efficiently to studying active processes, in particular through future use of existing boreholes. The acquisition of time series of in-situ measurements can be performed with CORKS, and by multiple reentries with wireline logging tools, operations that generally do not require the use of a drill ship (e.g., Becker et al., 2004). Only a few of existing reentry basement holes have been or are currently used as observatories (see maps in presentation by K. Becker, appendix D). Studying active processes also requires integration of geological and geophysical site studies with drilling and borehole measurements. For example, the analysis of micro-earthquakes provides insights on the hydrothermal system at 09°50'N on the East Pacific Rise (Tolstoy et al., 2008), which are complementary to core and borehole measurements.

Ocean bottom seismograph observations can provide hitherto unknown measures of the extent of recharge and discharge areas, and clear indication that the dominant pathways for axial hydrothermal circulation are parallel to the strike of the ridge axis. The analysis of tidal triggering of micro-seismicity provides independent constraint on upper crustal permeability, a critical parameter for modeling hydrothermal systems.

Breakout Sessions #2

Group 2A– Lower crust and Underlying Mantle
Group 2B– Heterogeneous mantle, associated geologic/biologic properties
Group 2C– Maturation of the lithosphere & its ecosystems
Group 2D– Monitoring active processes; along-strike variability

Plenary Discussion #3

A representative from each of the four breakout groups summarized outcomes of their discussion. These are summarized in the next section, with Groups 2A and 2D combined under "Initial Conditions". Group 2B outcomes are described under "Mantle on the seafloor: the serpentinite sea". Outcomes of Group 2C are given under "Maturation Processes". Following the breakout group summaries, a general framework for ocean lithosphere efforts within a new ocean drilling program was discussed. The session completed with discussion on the desirability of developing a statement to encapsulate scientific interest in deep drilling and recovery of mantle from beneath a representative crustal section (see "Concluding Remarks").

Outcomes of the breakout sessions

The ocean lithosphere is the principal process zone for interplay between the deep Earth and our planet's surface envelopes, and hosts key environments for fundamental magmatic, thermal, hydrologic, and biological exchanges in the Earth system.

Understanding the Initial Conditions

Understanding mantle melting and accretionary processes at oceanic spreading centers continues as a long-term goal in the geological sciences. Past/planned ocean drilling does indeed provide valuable results toward that goal. However, while additional progress in this traditional vein would surely advance understanding, this workshop sought to tease out aspects where truly new insight about the Earth System processes could be obtained with future ocean lithosphere (basement) drilling. Characterizing the igneous and metamorphic petrology, the related structures and physical properties remains an important goal; understanding the controls of seawater circulation and the role of biological processes in chemical exchanges become an integral part of the quest.

The vast majority of the magma generated within the Earth cools and crystallizes in the lower crust of the oceanic lithosphere. Yet there remain many open questions about the accretion processes that occur in the lower ocean crust, and this uncertainty affects our estimates of cooling rates and the heat available to drive interactions with the hydrosphere. One of the most compelling aspects of achieving a full-section penetration through fast-spread crust and into the mantle is to be able to address this gap in knowledge. Specific questions that full-sequence lower crustal drilling would address include:

- How and where is melt delivered, from the mantle to the upper axial melt lens?
- Does melt evolve through reactive processes and/or through fractionation processes?
- What is the composition of the entire crust and how are elements partitions between the lower cumulate crust and the upper crust?
- What causes ridge segmentation? This question may be addressed by along-strike drilling that allows assessment of center-segment versus end-segment differences in petrology and physical processes.

- What are the extents and mechanisms of hydrothermal circulation? Is cooling dominantly conductive or advective? What are the cooling rates within the crust and uppermost mantle?
- How does seismic velocity vary with depth in the lower crust, and what does this imply about the geometry of accretion?
- Is there evidence for off-axis magmatic additions to the lower crust?
- Is there evidence that faults and large fractures dominate the hydrology of the crust? Do these features provide avenues for the advection of ocean derived geochemical tracers and microbial populations?
- What is the wider influence of biological processes on the hydrologic properties of the oceanic crust?
- What is the depth limit of deep biosphere and geobiological processes in the lithosphere? Are the mantle and overlying crust hydrologically and biologically connected?

The penetration of a full-section crustal section down into the mantle, would allow fundamental, long-standing old hypotheses to be tested for the first time:

- Is the Moho a petrologic boundary and/or an alteration front? Are there significant bodies of ultramafic cumulate rocks formed by igneous processes within the crust? Does the seismically defined Moho signify the boundary between the igneous crust and the residual peridotitic mantle?
- Is the crust/mantle transition in intact ocean lithosphere a sharp boundary and/or an irregular zone with variable proportions of mafic/ultramafic igneous rocks and mantle peridotites?
- Does hydrothermal alteration of gabbro or peridotite influence the location and nature of the Moho in some regions?
- Is seismic anisotropy of the uppermost mantle the result of flow-induced alignment of peridotite minerals?
- Do abyssal peridotites provide a representative view of mantle/melt processes?

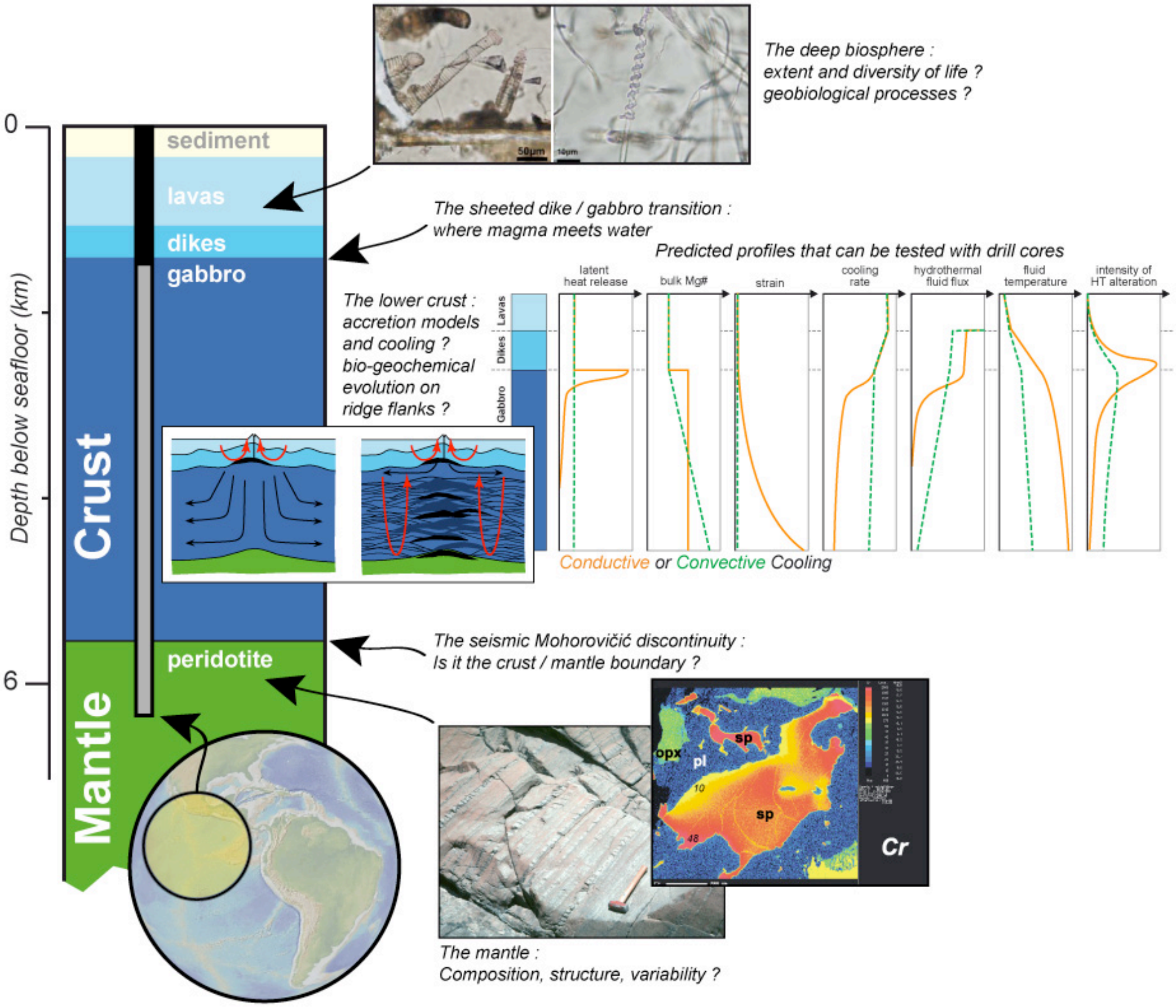

Figure 1: Schematic cross-section of fast-spread crust with anticipated MoHole penetration. The thicknesses of sediment, lavas and sheeted dike complex are taken from ODP/IODP Hole 1256D (Teagle et al., 2006). Top photographs: microbial ichnofossils in basalts from the Troodos ophiolite (McLoughlin et al., 2009). Predicted physical/chemical profiles in the crust: original figure from Rosalind Coggon; lower crust accretion models: after Korenaga and Kelemen (1998). Bottom photograph : layered harzburgites from the Oman ophiolite (photo Benoît Ildefonse). The chromium content map of impregnated abyssal peridotite shows extreme disequilibrium between melt and residue at infra-millimeter scale (Von der Handt et al., in revision). Figure by Benoît Ildefonse.

A major goal of studying active processes in young ocean crust is to understand hydrothermal fluid flow, which controls heat and chemical fluxes as well as the diversity of ecosystems. Specific questions centered on understanding fluid flow in new ocean lithosphere include:

- Fluid pathways near the spreading axis
  - What is the principal geometry of hydrothermal fluid flow (e.g., along axis? What is the depth of fluid penetration?)?
  - What determines where recharge/discharge occurs?

  - Are fluid recharge and/or discharge fluxes dominated by faults, fractures, or smaller-scale permeability structure? What is the 4-dimensional variability of permeability?

- Ore deposit formation
  - What are the controlling processes of massive sulfide deposit formation, how do they vary between difference geologic settings (e.g., backarc versus mid-ocean ridge; sedimented versus bare-rock ridges)?
  - What determines the settings and conditions where concentrations reach a level for viable human resource exploitation of ocean floor deposits?
  - What role does episodicity play in determining the structure of very large deposits?
  - Are microbial processes involved in enriching/modifying ore deposits?

- Extent of the subsea biosphere
  - How deep does microbial life extend and how does activity/diversity vary with depth in the oceanic basement?
  - What is the interplay between microbes, hydrothermal alteration and seafloor weathering?
  - What novel metabolisms/physiologies/enzyme activities may be present/active in the lithosphere? Do they have biotechnological potentials?

The monitoring of active processes at the ridge crests could measure timescales of axial volcanism and tectonic events. For example, drilling through an active detachment fault would enable measurements of fluid flow within the fault and analysis of strain-localization processes, both of which would advance understanding of fault processes in general. The additional aspect of aseismic slip may also be relevant in this type of setting.

The experimental approaches discussed emphasized integrative investigations that incorporated components of geophysical, geo-hydrological, and biogeochemical studies. The deployment of geophysical sensors in deep holes, cross-hole permeability experiments, and exploiting drill holes as ‘natural laboratories’ to monitor axial spreading centers, or to host mineral or microbial experiments are all innovative approaches that would add significant value to basic drilling experiments. Repeated logging is a key strategy to better estimate the volcanic stratigraphy and the extent of hydrothermal alteration of the crust. Directional drilling was highlighted as a possible means to sample areas overlain by difficult-to-drill fractured basalt. The ability to drill/log/monitor/ and sample fluids and gases in high temperature conditions is required to address several of the questions of interest for active processes. Sidewall coring should also be considered.

Mantle on the seafloor : the "serpentinite sea"

The occurrence of mantle rocks on the seafloor along slow-spreading ridges has been recognized for decades in the Atlantic. However, the understanding that detachment faulting is a major accretion process at slow- and ultraslow spreading ridges (e.g., Cannat et al., 2006; Smith et al., 2008; Escartin et al., 2008b) is very recent and emphasizes the importance of mantle on the seafloor. Offset drilling a few-100 m holes in mantle-dominated areas could address fundamental questions about mantle heterogeneity, and the development/evolution of detachment-dominated ocean ridge spreading. Understanding serpentinization processes, and constraining further the role of serpentinites in a variety of tectonic, hydrologic, chemical and biological processes are areas of research that ocean drilling can significantly advance.

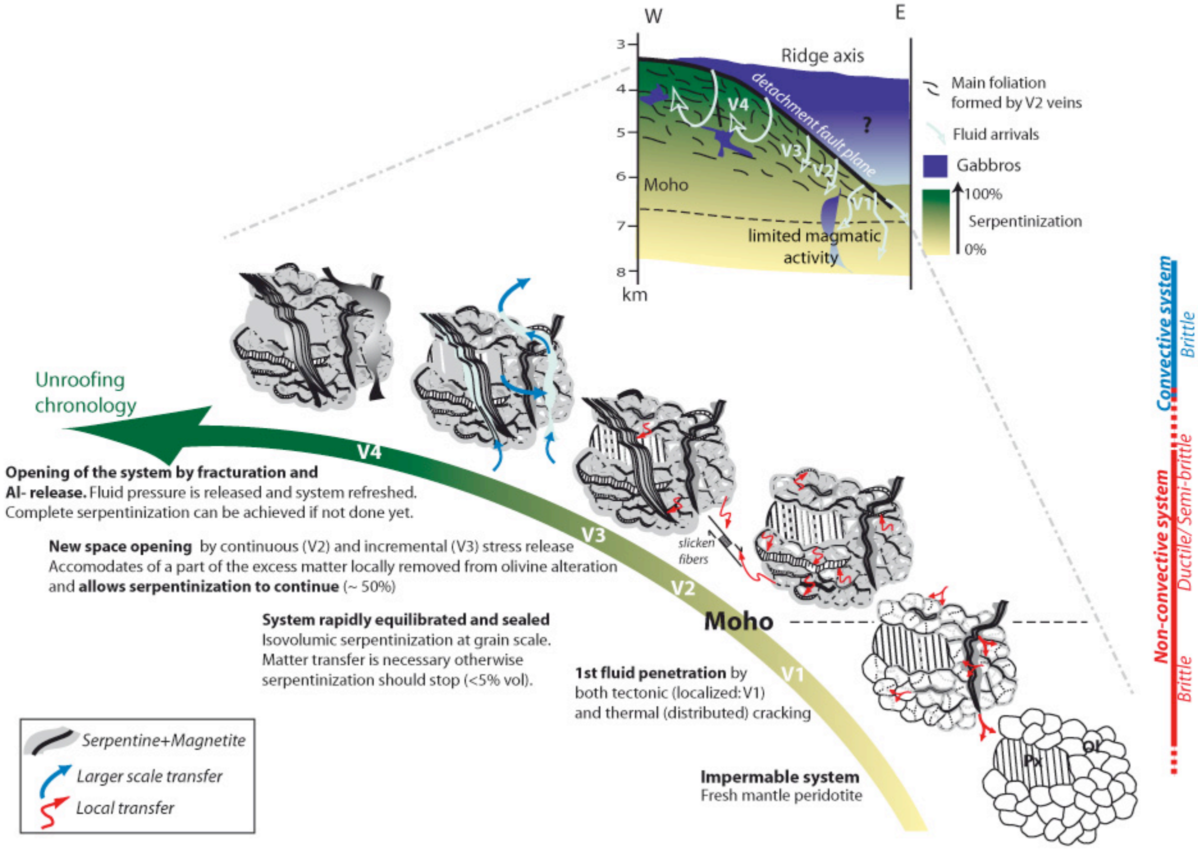

Figure 2: Serpentinization and detachment faults. Proposed model of serpentine vein formation and hydrothermal circulation during the progressive unroofing of peridotites exposed in the MARK area (from Andreani et al., 2007).

Serpentinization is the dominant reaction process that directly results from the occurrence of mantle rocks in the upper lithosphere, and a major process for hydration of the newly formed lithosphere (e.g., Kerrick, 2002; Bach et al., 2004). Serpentinites have low density and shear strength, hence they are expected to play a key role in detachment faulting, and in the interplay between faults and fluid flow at various scales. Serpentinite-hosted hydrothermal vent sites are a major discovery of the past decade (e.g., Kelley et al., 2001, 2005; Charlou et al., 2002). These sites are significantly different to those in volcanics-hosted systems, with distinct fluid chemistry and fauna. They are favorable sites for the production of hydrogen, and of abiotically generated hydrocarbons. Serpentinization is also associated with carbonation reactions, with a significant potential for carbon sequestration that warrants further investigation (Kelemen and Matter, 2008).

Fundamental questions that could be addressed by drilling in regions of seafloor mantle exposures include:

- What is the role of the serpentinization of mantle peridotites in the initiation and localization of ocean spreading on large-scale detachment faults?
- Does serpentinization requires high temperature melt-driven hydrothermal circulation to achieve the ~300°C reaction temperature? Is serpentinization spatially related to gabbro intrusions?
- What is the extent and distribution of serpentinization at depths greater than currently explored by drilling (~100 meters)?
- Does serpentinization impose an integral control on the nature and diversity of some deep-sea ecosystems? Are these systems inhabited by hydrogen- and hydrocarbon-utilizing microorganisms uniquely adapted to alkaline conditions? At least a fraction of the hydrocarbons is produced abiotically from reduction of CO_2 by H_2. Targeted deep biosphere drilling of active serpentinization systems would test this.

Drilling and borehole monitoring can also contribute to answer more general questions about serpentinization, such as:

- What are the timescales of serpentinization (~weeks in laboratory experiments, but what is it in-situ)? Providing an answer to this question will be important for assessing ways of CO_2 sequestration in ultramafics
- Can serpentinization rates be monitored in an actively reacting site, through the monitoring of reaction tracers in peridotite-hosted high-temperature vents? This would require an integrated experiment that

in addition to drilling would need geophysical mapping to assess the volume of rock involved in the process and potentially OBS microseismicity data to track the development of the a serpentinization front.

Focusing in on carbon, the deep carbon exchange has recently been highlighted by ophiolite studies of carbonated peridotite (Kelemen & Matter, 2008). Such investigations need to be extended to the vast oceanic seafloor mantle exposures. The discovery that large areas of the ocean crust are composed largely of serpentinized peridotite raises the question of how much carbon is naturally sequestered during off-axis sub-sediment fluid circulation. Actively serpentinizing/carbonating vent sites, such as the Lost City (Kelley et al., 2001) and Rainbow (Charlou et al., 2002; Ildefonse et al., 2008) hydrothermal vent fields provide opportunities to directly quantify this.

Research on carbon sequestration in subseafloor peridotite sections is underway. Experiments on rates of uptake and the viability of enhancing rates through addition of catalysts are seriously being considered (see presentation by P. Kelemen, appendices C and D). Much insight could be gained from increased understanding of fluid rock reaction pathways and rates, and their dependencies on temperature and rock composition. Ocean drilling offers the opportunity to undertake experiments within the seafloor to determine in situ CO_2 uptake rates.

Likewise, the production of hydrogen (and hydrocarbons) in serpentinization systems and its control on microbial populations can be assessed by similar means.

What is the nature and origin of heterogeneous lithosphere? What controls it? Characterization of newly formed ("zero-age") detachment-dominated lithosphere would address the key factors that cause at least 25% of slow and ultraslow spread new lithosphere to form this way. Comparison to magma-dominated slow-spread sections would be required to fully address this question.

Recent geologic and geophysical investigation of oceanic core complexes at Kane Megamullion in the Atlantic (Dick et al., 2008), and Godzilla Megamullion in the western Pacific (Ohara, 2006) have produced very similar interpretation of basement structure and composition in areas of heterogeneous crust. Several drill holes ~400-m deep in areas of strongly contrasting seismic character in such a core complex would ground-truth this connection. This would then validate the combined use of these techniques to map out the diversity of the crust exposed in different core complexes without further drilling, essentially leveraging a single drilling leg to validate a new approach for investigating the nature of the lower crust.

An example of a potential link between magmatic, metamorphic, and tectonic processes is the effect of melt impregnation of peridotite, which changes the system composition such that talc and chlorite form at temperatures whereas unimpregnated peridotite would not hydrate (e.g., Jöns et al., 2009). Local formation of mechanically weak rocks could hence capture strain throughout much of the lifetime of a detachment fault.

Drilling into actively serpentinizing regions in areas of detachment-dominated rifting will not only improve understanding of this process, and its scales of variability, but can also provide a natural laboratory for improving estimates of the variability in hazard associated with dehydration, deformation localization and the generation of large versus slow-slip earthquakes in subduction zones.

Finally, drilling in seafloor mantle exposures would address the following questions regarding mantle heterogeneity:

- Is heterogeneously depleted mantle recirculated and then remelted at oceanic spreading centers, and/or is homogeneously depleted mantle heterogeneously refertilized?
- Does eclogitisation of crust help to homogenise the mantle? To what extent does the depleted mantle persist independently?
- How does shallow mantle composition change with depth – are there significant chemical and physical gradients that reflect the geometry of mantle melting, melt flow, and mantle corner flow beneath ridges?

Following the Maturation Processes

Two overarching themes capture the aims of this thread of ocean lithosphere research that can be investigated by drilling:

- To understand and quantify the chemical, thermal, and biological exchanges between the oceans and the oceanic lithosphere: What are the integrated effects over time and what processes control these exchanges?
- What are the inter-relationships between ocean chemistry, ocean sedimentation, and crustal evolution over geological time and their impact on global biogeochemical cycles?

Questions to addressed by the 1st theme are:

- What is the balance of inorganic and biomediated alteration as a function of age?
- What are the relative controlling roles of spreading rate, lithospheric architecture and sedimentation in crustal evolution?

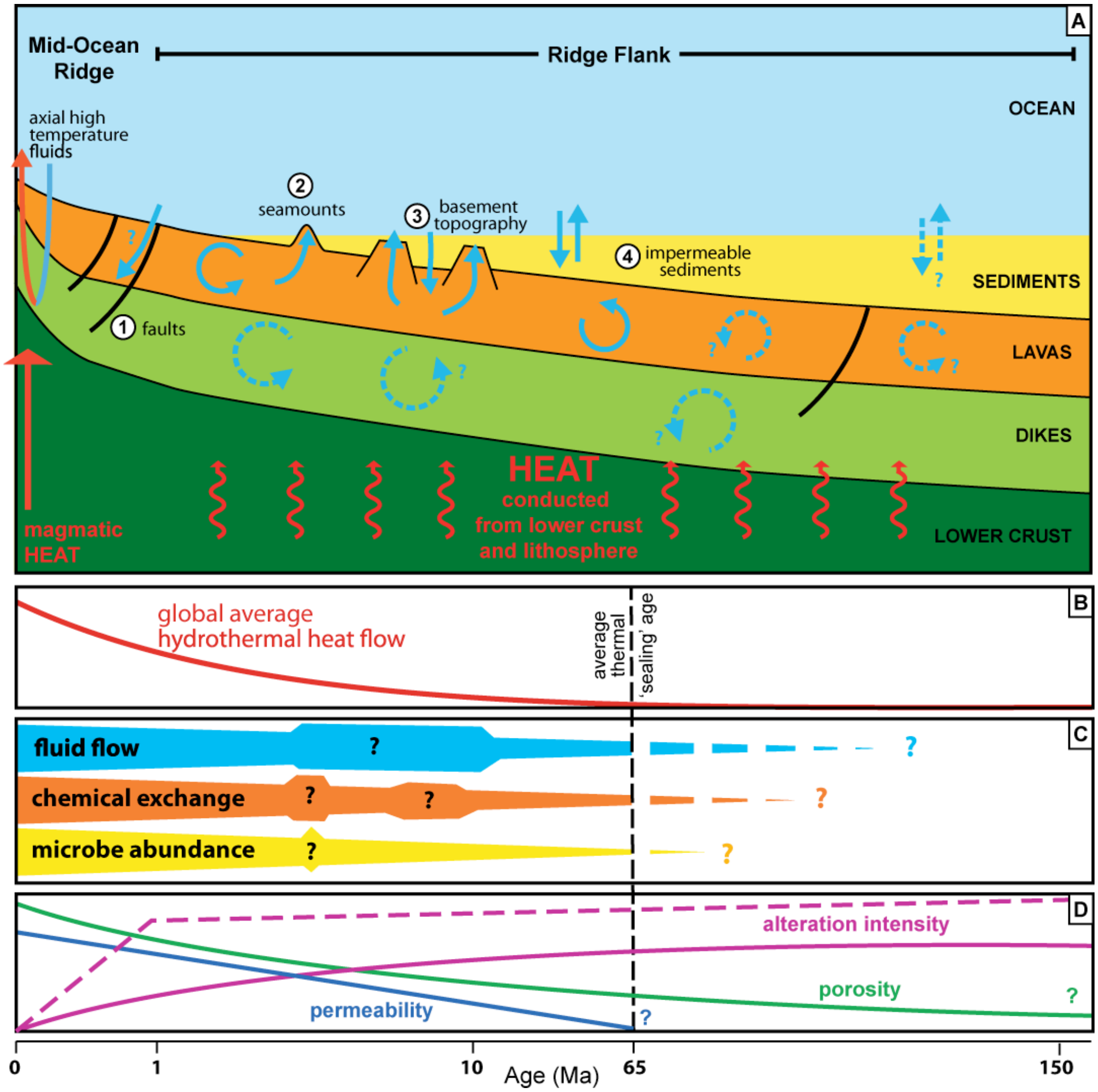

Figure 3: Maturation of the ocean crust. A cartoon showing the schematic architecture of a mid-ocean ridge flank (**A**; not to scale), illustrating parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as (1) faults, which may channel fluids, (2) seamounts, which can act as permeable 'short-circuits' between the crust and ocean, (3) basement topography, which can produce sufficient differential fluid pressure to drive fluid flow, and (4) impermeable sediments, which isolate the crust from the oceans. Arrows indicate heat (red) and fluid (blue) flow. The calculated global hydrothermal heat flow (**B**; the difference between the average measured conductive heat flow and that predicted from conductive cooling plate models) decreases to zero, on average, by 65 Ma. At this age the crust is typically assumed to be 'sealed' to hydrothermal circulation. However, global averaging removes much of the heat flow signal from local effects (e.g., basement topography) and fluid flow, chemical exchange and microbial activity may persist in ridge flanks of all ages. **C**; The effects of parameters such as basement topography and sediment thickness on their intensity and relative cessations remain undetermined. The hydrological, physical, chemical and biological evolution of hydrothermal circulation through the ridge flank could be investigated by an integrated research program comprising surveys (mapping, seismic surveys, and heat flow studies), drilling, and subsequent borehole testing, sampling, in situ experiments and monitoring, across a ridge flank. **D;** The controls on the intensity and style of hydrothermal circulation could be investigated by the measurement of multiple parameters such as porosity, permeability, and alteration mineralogy. Figure by Rosalind Coggon.

- What are the relative cessations of fluid flow, microbiological activity, and alteration, and how are they interrelated?
- How does microbial biogeography vary spatially and temporally in the ocean crust?

The 2nd theme questions are formulated as follows:

- What does the record of crustal alteration resolve about past ocean chemistry and the controls on ocean chemistry?
- Can we use the record of ocean chemistry as a benchmark to compare the wider biochemical cycles of the Earth system?

Integrated survey and drilling studies will be used to evaluate controlling factors and resultant effects. Potential controlling factors include crustal age, initial crustal architecture, history of spreading rates, sedimentation history, basement topography, basement permeability, faulting, and ocean chemistry. Potential measurable effects include the nature and degree of alteration and microbial activity in cores, surface heat flow, crustal seismic velocities and their spatial variations, and spatial variations in magnetization.

Generic drilling experiments that could achieve these goals include:

- Detailed study sites at well-surveyed locations along age transects, e.g., holes spaced at 10-20 My intervals along the Atlantic crustal flow line between DSDP Holes 395A/418A, and a similar fast-spread crust transect.
- Opportunistic basement drilling along paleoceanographic age transects (e.g., IODP PEAT expeditions 320 & 321).
- Comparative sites where controlling factors are known to vary, either locally or regionally (e.g., ODP Holes 504B and 896A).
- Paired-hole studies (or 2-D arrays) at lateral spacings of ~1 km.

Concluding remarks : a general framework for ocean lithosphere efforts within a new ocean drilling program

The compositional and structural heterogeneity of the oceanic lithosphere arises from temporal and spatial variations in mantle composition and thermal structure, magma supply, efficiency of melt extraction, tectonic extension, or a combination of any of these factors. Drilling is a fundamental and critical tool for understanding the origin, scales, and implications of such heterogeneity. For many fundamental Earth science questions drilling is the only possible approach to recover samples, on which analyses and observations can be conducted to test competing hypotheses of how our planet works. However, the global relevance of the geological processes inferred from the one-dimensional view that deep drilling provides must be tightly integrated with other regional observations to fully understanding the complex, three-dimensional nature of the context where drilling takes places. This is particularly true when considering drilling a full crustal penetration to the Moho and well into the underlying upper mantle, which, if as planned, will be initially attempted in a single site. Improved understanding of the ocean lithosphere can only be achieved by integrating and ground-truthing drilling observations in different geologic settings with detailed morphological and seafloor geological mapping, and with geophysical imaging of the sub-seafloor heterogeneity at spatial scales that are comparable to those of seafloor observations.

The ocean lithosphere community has a strong record of science-driven technology development (e.g., CORKS). The fundamental and challenging science questions outlined in this report will be a major incentive for continued technological development and innovation. It is hoped that the full suite of available and next-generation technological capabilities will be used to optimize scientific return in ocean lithosphere drilling efforts. This includes, for example, D/V Chikyu, seabed rock drills, CORKS, the capacity to drill fractured basalts, the monitoring of and fluid/gas sampling in boreholes in high-temperature environments, borehole experiments (e.g., cross-hole experiments, VSP), borehole-hosted laboratories and instruments (e.g., microbe culturing), improved wireline tools, mud logging (cuttings analysis, fluid/gas monitoring), sidewall coring. As the need to drill and core a full intact section of ocean crust to the Moho and into the upper mantle is re-affirmed, we strongly endorse development and continuation of efforts to assess and design coring and borehole characterization capability that enable coring, measurement and sampling at high temperatures, in very deep holes and in great water depths.

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Links to earlier planning documents

- Woods Hole workshop report, 1996 :
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Appendix A - Workshop Agenda

Day 1: Monday, 27th July, 2009: NOCS Charnock Lecture Theatre

08:30 **Welcome from Professor Sir William Wakeham, Vice Chancellor, University of Southampton** **Damon Teagle** (NOCS), **Benoit Ildefonse** (CNRS-Montpellier)
Workshop Introduction: Meeting Overview and Objectives

Keynote Lectures: Formation and Evolution of the Ocean Crust:
What we know and what we need to know

09:00 **Eric Hellebrand** (Hawaii)
Why we need Spatially Controlled Sampling of the Oceanic Mantle

09:30 **Shuichi Kodaira** (IFREE, JAMSTEC)
Geophysical characteristics of oceanic crust, mantle and Moho in the western Pacific

10:00 – **Tim Henstock** (NOCS)
Theoretical and geophysical evidence for the mechanisms of formation of the (lower) ocean crust

10:30 ***Coffee/Tea*** (Exhibition Area)

10:45 **Mathilde Cannat** (IPGP-CNRS)
Contrasting the architecture of ocean crust formed at fast and slow spreading rates

11:15 **Johan Lissenberg** (Cardiff)
Magmatism at mid-ocean ridges: A lower crustal perspective

11:45 **John Sinton** (Hawaii)
Chemical heterogeneity in MORB: influences of melting, reaction in the mantle and crust, and fractionation

12:15 **Mike Cheadle** Summation of morning session

12:30 ***Lunch*** (Exhibition Area)

13:30 **Kathy Gillis** (Victoria)
Heat and chemical exchange by hydrothermal processes: The hydrothermal alteration record

14:00 **Steve Roberts** (NOCS)
Mechanisms for the formation of ocean floor massive sulfides: Is there more to learn from ocean drilling?

14:30 **Rob Harris** (OSU)
The Subseafloor Ocean: Evolution of Hydrothermal Circulation

15:00 **Roz Coggon** (Imperial College)
The impact of ocean basement alteration on global chemical cycles

15:30 ***Coffee/Tea*** (Exhibition Area)

15:45 **Katrina Edwards** (USC)
Coupled microbiological, geochemical, and hydrological studies in ocean crust - alteration, weathering, and long-term CORKed observatories

16:15 **Fumio Inagaki** & **Yuki Morono** (JAMSTEC-Kochi)
New analytical technologies for the deep subseafoor life

16:45 **Laurence Coogan** Summation of Afternoon Session

17:00 ***Discussion and Evening Poster Session w/refreshments*** (Exhibition Area / Seminar Room)

Day 2. Tuesday 28th July, 2009

In-depth discussion within individual topical groups

08:30 **Plenary Session to set goals for discussion: (**NOCS Charnock Lecture Theatre)

- recognize areas of consensus on current understanding,
- explore areas where different viewpoints persist and identify experiments to reconcile them
- identify processes that we have no/little real understanding of but that are crucial for understanding mid-ocean ridge processes and their impact on the wider Earth system.

Aim to identify 6 to 8 themes to be explored by morning and afternoon break out groups

10:30 ***Coffee/Tea*** (Exhibition Area)

10:45 **Breakout sessions:** Individual topic discussions (3-4 groups)
(NOCS Charnock L/T, Seminar Room, Exhibition Area, 064 Node Room)

12:30 ***Lunch*** (Exhibition Area)

13:30 **Plenary session** with 5-min summary by each topic group **(**NOCS Charnock Lecture Theatre)

14:00 **Breakout sessions:** Individual topic discussions (3-4 groups)
(NOCS Charnock L/T, Seminar Room, Exhibition Area, 064 Node Room)

15:30 ***Coffee/Tea*** (Exhibition Area)

15:45 **Plenary session** with 5-min summary by each topic group **(**NOCS Charnock Lecture Theatre)

16:00 **Oral Session – Short talks on advances in mid-ocean ridge science and deep drilling technologies**
Shin'ichi Kuramoto and **Masaoki Yamao** (CDEX, JAMSTEC)
The Chikyu Enhancement Plan - Road to the Mantle

16:20 **Greg Myers** (IODP-MI)
Engineering to Support Transformative Science - Ultra-deep drilling in Hyper-Deepwater

16:40 **Maya Tolstoy** (LDEO)
Implications for mid-ocean ridge hydrothermal and magmatic processes from microearthquake data at 9°50'N East Pacific Rise

17:00 **Tony Morris** (Plymouth)/**Masako Tominaga** (TAMU)
Advances in core-log correlation using Formation MicroScanner imagery: core reorientation and lithostratigraphy in hard-rock IODP drill holes

17:20 **Keir Becker** (Miami)
Maximizing the value of existing crustal holes by reentry from IODP drillships or oceanographic vessels

17:40 **Wolfgang Bach** (Bremen)
Metasomatic mass transfers in heterogeneous ocean crust: New insights from recent basement drilling

18:00 **Break for Drinks and additional time for posters** (Exhibition Area / Seminar Room)

18:15: **Peter Kelemen** *(LDEO)* **Keynote Lecture (**NOCS Charnock Lecture Theatre)
In situ mineral carbonation in peridotite (and basalt?) for CO_2 capture and storage

20:00 **Conference Dinner – Olive Tree Restaurant, Oxford Street, Southampton** (10 minutes walk away)

Day 3. Wednesday 29th July, 2009

Focus on how future drilling or in-situ monitoring can address key questions

09:00 **Plenary Session to set goals for discussion: (**NOCS Charnock Lecture Theatre)

- Identify key outstanding problems that can only be tackled by drilling
- Clarify how drilling can address processes and/or quantify exchanges
- Discuss uncertainties that would remain if current technology is used
- Discuss whether there are technological improvements viable within the coming decade that would decrease uncertainties in measurements

10:30 ***Coffee/Tea*** (Exhibition Area)

10:45 **Breakout sessions:** Individual topic discussions (3-4 groups)
(NOCS Charnock L/T, Seminar Room, Exhibition Area, 064 Node Room)
(Drilling- offset & deep, In-Situ Monitoring, Contextual studies

12:30 ***Lunch*** (Exhibition Area)

13:30 **Plenary session** with 10-min summary by each topic group **(**NOCS Charnock Lecture Theatre)

- Full-group discussion of consensus points for further discussion at INVEST
- Identification of points that need additional development prior to INVEST

15:30 ***Coffee/Tea*** (Exhibition Area)

End ~16:00 – 17:00

Appendix B -Workshop Participants

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Appendix C – Abstracts of lectures, posters and white papers

Abstracts for Keynote Lectures

in order of presentation
27th July, 2009

Why we need Spatially Controlled Sampling of the Oceanic Mantle

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Department of Geology and Geophysics, University of Hawai'i, Honolulu, USA

In the past two decades, we have made tremendous progress in our understanding of partial melting and melt migration processes that occur in the upwelling mantle underneath mid-ocean ridges. Direct information on these aspects of the partial melting process can only be obtained on peridotites, the residues of melting. Mineral and whole rock compositions of mantle peridotites change systematically during the removal of basaltic components, leaving behind a pyroxene-poor and olivine-rich residue that is generally strongly depleted in incompatible trace elements. Trace element compositions of pyroxenes suggest that the melt extraction mechanism is dominated by efficient melt removal and focused melt transport, rather than widespread diffuse melt percolation, although numerous counterexamples have been found in recent years. Trace elements also support that melting commonly initiates at high pressures in the stability field of garnet peridotite. Furthermore, we can quantify the amount of partial melting and the melt porosity during partial melting, assuming a homogeneous peridotite starting composition widely known as the Depleted MORB Mantle (DMM).

Until recently, the main open issues seemed only to be related to the scales, distribution and causes of chemical heterogeneity that remain after we have filtered for low-temperature alteration effects and late-stage magmatic overprints (i.e. plagioclase- and vein-bearing peridotites). However, recent isotopic studies, most notably using the rhenium-osmium decay system, have revealed that a relatively large fraction of the accessible oceanic mantle has an old (1-2 billion years) depletion signature inherited from partial melting events. We have also found extremely depleted peridotites in the (virtual) absence of magmatic crust, as well as dredge-scale coexistence of highly depleted and very fertile peridotites. Possibly as much as 20% of the upper mantle may be significantly more depleted than DMM, prior to upwelling and melting under a mid-ocean ridge. Since peridotites previously depleted in basaltic components do not contribute substantially to MORB generation. Thus, their geochemical signal cannot be inferred from MORB studies and are thus invisible in erupted basalts. An important implication of widespread preexisting depletion prior to recent upwelling under the ridge is that quantitative melting models and porosity estimates are less well constrained as we currently believe.

How can IODP help to resolve these open questions? Past drill holes in mantle rocks (ODP Legs 147 and 153) recovered remarkably homogeneous peridotites. ODP Hole 209 drilled into old depleted peridotites, overprinted recently by migrating melts. In combination with continued detailed dredging-based mantle petrology and geochemistry, we need at least one or preferably several drill holes into near-seafloor mantle peridotites that display substantial local-scale heterogeneity. This will enable us to study the abundance and distribution of old inherited peridotites and their interaction with the surrounding mantle during upwelling, partial melting and melt migration. This knowledge is necessary before tackling the long-term goal of drilling into the mantle through a normal magmatic crustal sequence. As opposed to the accessible near-seafloor mantle that is characterized by low melt supply, a mantle overlain by normal magmatic crust may have its preexisting heterogeneities rehomogenized by high melt-peridotite ratios.

Finally, abyssal peridotites are not representative of the top of the melting column in areas of normal crust thickness and give us an important but distorted view of the partial melting process. For a less distorted crust-mantle mass balance, it will be of crucial importance to drill significantly beyond the Moho, and take this objective into account for the long-term planning of Mission Moho.

Geophysical characters of oceanic crust, mantle and Moho in the western Pacific

Shuichi Kodaira
Institute for Research on Earth Evolution,
Japan Agency for Marine-Earth Science and Technology

Lithosphere structure imaging group in JAMSTEC has conducted active- and passive-seismic studies in subduction zones around Japan. Those studies provided several new findings for understanding earthquakes and crustal evolution processes. For example, dehydration from subducting oceanic crust may cause a slow slip monitored at down-dip end of the Nankai seismogenic zone. Moreover, a series of active-source seismic studies in the Izu-Bonin subduction zone clearly demonstrates that crustal volume of arc crust strongly varied along the 1000 km-long intra-oceanic arc system in either a shorter wavelength (i.e., volcano distribution scale) and a longer wavelength scale (i.e., Izu vs. Bonin). Those variations are interpreted to be attributed by variations of input materials, like fluid and/or magma, which are originated from subducting oceanic crust. A fundamental question was arisen from those studies; i.e., structure and composition of incoming plate to subduction zone may play a key role to control geodynamical and geochemical processes in subduction zones. In order to address this question, recently our group started a new project for investigating seismic structure of incoming oceanic lithosphere. This paper mainly presents seismic images of oceanic crust, mantle and Moho of the western Pacific which was processed under cooperation with the Coast Guard Japan. Data I present are wide-angle and multichannel reflection seismic data acquired around the Marcus-Wake seamount chain which was overprinted on the world oldest Jurassic oceanic basement in Cretaceous time. A seismic velocity image along a 900-km long profile shows that seamount-related mafic crust only observed 20 – 30 km wide around each seamount. On the other hand, uppermost mantle velocity is reduced down to 7.6 km/s over 500 km wide to cover entire the Marcus-Wake seamount chain. At the both side of this profile, the seismic line extends on the Jurassic oceanic crust, but tectonic histories of crust at the both side is different; i.e., the northern and southern parts were formed along the Pacific-Farallon boundary and the Pacific-Izanagi boundary, respectively. The crustal thickness and reflectivity character of the both parts are remarkably different. For example, a layered Moho reflection signature is observed at the southern part, but more obscure or scattered Moho is imaged at the northern part. A surprising seismic data are acquired along another profile on the Jurassic oceanic crust. The uppermost mantle velocity along the profile perpendicular to the magnetic anomaly is estimated to be more than 8.6 km/s with 10 % anisotropy. In addition to the review of the detailed seismic character of oceanic crust, mantle and Moho of the Marcus-Wake profiles, I will present preliminary results of numerical simulation of reflection character of the Moho to understand relations between seismically imaged Moho and petrological observation of crust-mantle transition zone.

Forming the lower ocean crust – a (geo)physical view

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Geophysical observations are the only way to obtain direct in situ information about the lower crust at fast-spreading mid-ocean ridges: Seismic reflection images show a thin (~10's-100 m) and narrow (100's-1000 m) sill-like feature at shallow depths (1-2 km) which varies along axis between being entirely molten and mushy; seismic refraction experiments constrain P-wave velocity anomalies on scales of 1 km through the rest of the crust to be less than 2-3 km/s; compliance studies suggest the presence of an S-wave low velocity zone in the 2 km immediately above the Moho, consistent with some exotic phases identified in ocean-bottom seismometer data.

Two end-members have been proposed for the accretion of the lower crust – either by intrusion and solidification at a high level with subsequent deformation ("gabbro glacier") or by intrusion and solidification in situ ("sheeted sill"). These cartoons can be tested by constructing physical models to predict parameters such as temperature and melt fraction - or more conveniently, an observable such as seismic velocity; the key here is that because the models lead to specific predictions they are falsifiable. A robust conclusion of the geophysical experiments is that the majority of the lower crust is solid close to the axis; fairly simple physical models show that this requires either intrusion into the lower crust to be limited (gabbro glacier) or vigorous hydrothermal circulation to extend throughout the crust (sheeted sill). The sheeted sill concept therefore requires a minimum effective permeability in the lower crust to enable such circulation to occur.

Key unknowns include: How can measurable quantities (e.g., seismic velocity) be robustly related to model predictions (e.g., temperature)? What is the permeability structure of the crust at the ridge axis? Can we identify sections of mid-ocean ridge at which melt is being intruded at multiple depths (or equally exclude this by exhaustive data collection)? What about the different simplifications in all the physical models – has some critical set of physics been ignored?

Contrasting the architecture of ocean crust formed at fast and slow spreading rates

Mathilde Cannat
Institut de Physique du Globe de Paris, CNRS UMR 7154

Magmatism at mid-ocean ridges: A lower crustal perspective

Johan Lissenberg
Cardiff University

Melt transport from the mantle advects significant amounts of heat to the crust, which, augmented by the latent heat released during crystallization, forms the primary driver of hydrothermal systems. Location, frequency and size of melt additions are thus key parameters to constrain. Long *in-situ* sections recovered by ocean drilling indicate that slow-spreading lower crust is comprised of hundreds of small (m-scale) intrusions, which, on a larger scale, form intrusive cycles of hundreds of meters thick. The volume of melt in magma chambers indicates that melt delivery is episodic on a ±10 ka scale. Recent advances in zircon dating provide a tool to quantify emplacement depth of melts. Results to date suggest that at slow-spreading ridges some plutons may crystallize in the mantle, consistent with geological observations and thermal models. At fast-spreading ridges crystallization is generally confined to the crust, but the location of melt delivery remains debated, and the size and frequency of melt batches is uncertain. Cooling rates of the lower crust remain poorly constrained, but tools developed in recent years should result in significantly improved estimates within the near future.

The gabbroic rocks of the lower crust form the geochemical link between the mantle and mid-ocean ridge basalts (MORB). In order to understand how MORB compositions relate to melting processes and source composition of the mantle, then, it is critical to constrain how primary melts evolve in the lower crust. Fractional crystallization has traditionally been assumed to be the dominant – commonly even the only – mechanism, but evidence from the lower crust suggests reactions between rising melts and lower crustal lithologies are common. Pioneering studies have argued that such reactions may have significant effects on MORB compositions, but the extent of interaction, the length scale over which it takes place, and its geochemical signatures remain to be elucidated.

In order to advance knowledge of lower crustal processes, and their implications for the mass and heat transfer through mid-ocean ridges, scientific ocean drilling remains critical, as it allows access to subsurface geology, and provides the only means of recovering continuous sections, allowing studies at high spatial resolution.

Chemical heterogeneity in MORB: influences of melting, reaction in the mantle and crust, and fractionation.

John Sinton, Ken Rubin, Deborah Eason
University of Hawaiʻi

Global systematics of MORB compositions provide information on the role of magma chambers in reducing chemical heterogeneity of erupted magmas. High magma supply at fast spreading ridges stabilizes shallow magma chambers, which produce moderately to highly differentiated magmas. These magmas show a large variation in chemical attributes imparted by differentiation in the crust, but with narrow ranges of chemical attributes related to mantle source and migration-related reaction processes. In contrast, low magma supply promotes the eruption of more uniformly but less differentiated magmas that show a greater range of chemical attributes commonly attributed to mantle source variations. Thus the composition of erupted MORB is highly sensitive to the thermal state of the crust; magma MgO is much more strongly correlated with depth of last equilibration in the crust than with overall magma supply. Increasing magma supply allows magma reservoirs to stabilize to shallower levels, but this environment is highly sensitive to temporal variations in cooling rate.

Particular insight into the processes that contribute to MORB chemical heterogeneity have been gained from (1) studies of MORB at ridges that lack well-developed magma chambers, such as low-magma supply ridges and offsets at faster spreading ridges, and (2) comprehensive study of samples from single eruptive events that preserve the heterogeneity within underlying magma systems. Examples from these special settings indicate that (1) early clinopyroxene crystallization is a feature of many MORB suites, which can either be produced by relatively high-pressure equilibrium crystallization in the upper mantle or by disequilibrium reaction in the crust; (2) rapid supply from heterogeneous mantle can preserve a wide range of source signatures even in quasi-steady state magma chambers at very high spreading rates; and (3) crustal assimilation is promoted by long-lived, slow melt migration through the crust. Each of these processes can affect major and trace elements, and in some cases isotopic ratios, in ways that make the common inversion of MORB chemistry to mantle melting processes problematic.

Heat and chemical exchange by hydrothermal processes: The hydrothermal alteration record

Kathy Gillis
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University of Victoria

Understanding the magnitude and process that control heat and chemical fluxes that result from hydrothermal circulation has been an overarching goal of the lithosphere community for a few decades. These fluxes play a key role in the earth system, as they influence the rheology of the ocean lithosphere, composition of seawater, and chemical evolution of subduction zones, and provide the energy and nutrients for extremophile organisms. The ocean crust provides a record of the heat and chemical fluxes that is essential to test models based on theory, geophysical data and a variety of surface collected data (e.g., vent fluids). The ocean crust provides a time-integrated perspective that is complementary to the near instantaneous view of vent fluids and geophysical measurements. In this presentation, I will focus on the hydrothermal alteration record associated with basalt-hosted axial systems in two settings: the upper crust generated at intermediate- to fast-spreading ridges and the lower crust at slow-spreading ridges.

Great progress has been made in understanding alteration processes within the upper ocean crust, as there are four well studied areas: ODP Hole 504B, ODP/IODP Hole 1256D and Hess and Pito Deeps. While some details vary, the mineralogical and geochemical characteristics of the sheeted dike complexes at all locations record a stepped thermal profile that coincides with the lava-dike transition. The field data shows, however, that there is significant lateral variability that reflects temporal variability in the hydrothermal system. Fluid fluxes calculated using whole $^{87}Sr/^{86}Sr$ ratios are very similar for all locations ($1.5–2.6 \times 10^6$ kgm^{-2}), reflecting the heat and mass flux at mid-ocean ridges. The prediction that conductive boundary layers separate hydrothermal systems from the heat source that drives them has been confirmed by the identification of recrystallized sheeted dikes at the dike–gabbro transition at all locations. Incipient alteration of the uppermost gabbros occurs at high temperatures, with fluid flow along fracture networks occurring over very short timescales.

Oceanic core complexes (OCCs) provide access to the lower ocean crust that has been tectonically exhumed at the seafloor; two well studied areas are: the Atlantis Massif (Mid-Atlantic Ridge, IODP U1309) and Atlantis Bank (Southwest Indian Ridge, Hole 735B). The combination of regional scale geophysical and geological surveys with deep drill holes at these locations has greatly enhanced our understanding of the hydrothermal and tectonic evolution of these OCCs. We've learned, for example, that gabbroic rocks are variably altered and that detachment zones act to focus fluids at high and low temperatures and, locally, a high fluid flux.

We have make incremental steps towards understanding the heat and chemical exchange at mid-ocean ridges. To make further progress, we should focus our sampling programs on areas where we can obtain a 3-dimensional view, such as the tectonic windows afforded by, for example, OCCs and propagating rifts. We should also fully utilize the tremendous resource of existing cores and systematically apply conventional and new petrological and geochemical approaches to quantify processes such as cooling rates and chemical exchange.

Mechanisms for the formation of ocean floor massive sulfides: Is there more to learn from ocean drilling?

Stephen Roberts

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Ocean floor hydrothermal vent sites, with the associated formation of of massive sulfide deposits, play a fundamental role in the geochemical evolution of the Earth and oceans, are a key location of heat loss from the Earth's interior and provide insights into the formation of ancient volcanogenic massive sulfides. Furthermore, they are increasingly viewed as attractive sites for the commercial extraction of base metals and gold.

ODP drilling of sea-floor massive sulfides includes, Leg 158 TAG, Legs 139 and 169 Middle Valley and Leg 193 PACMANUS. Each of these drilling campaigns generated new information and fundamental insights into the formation of massive sulfides on the sea floor. Scientific highlights include the discovery and abundance of anhydrite in the systems; with estimates that the TAG mound contains about 165,000 metric tons of anhydrite. The formation and ultimate dissolution of anhydrite is also recognised as an important mechanism for the formation of sulfide breccias, which are typically observed in ancient massive sulfide deposits. Finally, stable and radiogenic isotope (^{87}Sr/^{86}Sr) analyses of anhydrite highlight the nature and extent of seawater circulation within the sulfide deposit. Leg 169 Middle Valley, achieved the first succesful recovery of feeder zone mineralization underlying a sea-floor massive sulfide deposit, the recognition of a deep copper zone and the mineralization of poorly consolidated sediments. This leg also highlighted the role of rift parallel faults in controlling fluid flow and sites of mineralization. Leg 193 PACMANUS, penetrated a ridge of andesite to rhyodacite lava flows, displaying coherent and brecciated facies and some volcaniclastic horizons. Stable, radiogenic isotope and REE analyses of anhydrite indicated that mixing between seawater and a high-temperature hydrothermal fluid, that itself has a component of seawater intermixed with fluids derived from igneous or magmatic sources at deeper levels, played a fundamental role in the development of the system. Fluid inclusions in anhydrites established that phase separation or boiling occurred in fractures that became veins and breccia matrixes within the pervasively altered volcanic sequence. The elevated porosity and permeability of the altered volcanic rocks facilitated diffusion during alteration processes, but fracturing remains the more important control on fluid flow.

Given these significant advances, is there more to learn and what should a future drilling campaign focus on? A key theme for proponents of further drilling of sea-floor massive sulfide systems is to extend drilling/logging downward, towards inferred intrusive bodies, and establish the petrological, geochemical and geophysical characteristics of the high-temperature reaction zones to these systems. Such information will lead to a better understanding of the nature of high temperture alteration, water-rock reaction, and hydrothermal fluid circulation. There are also aspirations to drill sufficiently deep holes between sites of hydrothermal activity to establish continuity, or otherwise, of alteration and mineralization patterns. For both these goals to be achieved the extent of core recovery and depth penetration are key issues to be resolved. Furthermore, during the lifetime of ODP, the recognition of massive sulfides associated with submarine arc volcanoes e.g. Brothers Volcano, Conical Seamount, provide examples of massive sulfide formation where the "3rd dimension" remains untested, yet such sites are presently the focus of scientific research and potential exploitation as a mineral resource. Indeed, these locations may provide the key evidence to resolve the open question of the the role of magmatic contributions to the metal budgets of volcanogenic massive sulfide deposits.

The Subseafloor Ocean: Evolution of Hydrothermal Circulation

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Seafloor hydrothermal circulation on ridge flanks extracts > 8 TW (~30%) of lithospheric heat and impacts many tectonic, magmatic, microbial and biogeochemical processes. At the global scale, the conceptual evolution of hydrothermal circulation is generally understood as a function of crustal age. In young oceanic lithosphere, hydrothermal circulation dominates heat transfer where thermal gradients are high, crustal permeabilities are high, and there are open pathways for seawater to enter and exit the oceanic crust. With the progression of time, heat loss by fluid flow is diminished as temperature gradients and crustal permeability decreases, and the accumulation of low permeability sediment isolates the crustal aquifer from the ocean. However, understanding the impact of hydrothermal circulation and its longevity on crustal processes require greater insight than that provided by conceptual models and global compilations of heat flow data viewed as a function of age.

Scientific drilling, well navigated transects of closely spaced heat flow measurements combined with environmental information from seismic and swath mapping, and pore-water geochemistry, are leading to an increased understanding of hydrothermal circulation. These local studies, while biased towards young crust, suggest that driving forces are low to modest, temperatures in the crustal aquifer can be extremely uniform, and that formation scale permeabilities remain high enough during the lifetime of oceanic crust to sustain hydrothermal circulation. Numerous local studies show the importance of basement relief, sediment thickness, completeness of sediment cover and spacing between exposed basement on the vigor, patterns, and degree of ventilation of oceanic crust. These environmental factors influence the balance between driving and impeding forces to flow. A continuing goal of hydrothermal circulation studies should be to: 1) quantify formation scale rock properties and state as a function of flow regime; 2) determine the balance between driving and impeding forces to flow; and 3) document the three dimensional rates and patterns of flow in open circulation, closed circulation, and the transition between these regimes.

The impact of ocean basement alteration on global geochemical cycles

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Hydrothermal circulation is a fundamental process in the accretion and aging of the ocean crust, influencing its structure, and physical and chemical properties. Drilled sections of altered ocean basement have therefore been important to the development of ocean crustal accretion models. Hydrothermal circulation is also a major component of global geochemical cycles. Consequently knowledge of the controls on the extent and nature of basement alteration, combined with observations of basement alteration in ancient ocean crust can tell us about changes in global-scale processes.

Seawater chemistry reflects the balance between the supply and removal of elements to and from the oceans. These fluxes are dominated by riverine inputs, hydrothermal exchange and sedimentary removal, and their magnitudes depend on key global geologic processes including plate tectonics, climatic conditions, and biological processes. Temporal variations in seawater chemistry can therefore provide insights into fundamental Earth processes. However, reconstructing reliable records of past seawater chemistry and de-convolving the processes responsible for temporal variations in such records remain major challenges.

Recent studies have demonstrated that altered sections of oceanic basement can be used both to reconstruct past seawater chemistry and to investigate the processes responsible for changing ocean chemistry. For example, the past seawater elemental concentrations required to produce observed shifts in the isotopic composition of ancient crustal sections can be estimated by simple mass balance, given independent (e.g. thermal) estimates of the fluid flux through the crust. Secondary minerals (e.g. calcium carbonate) that record the composition of the seawater-derived fluids that they precipitate from can also be used to reconstruct past ocean chemistry, provided the effects of fluid-rock exchange are accounted for. Furthermore, knowledge of how factors such as spreading rate, crustal age, and sedimentation history effect the nature and extent of hydrothermal alteration, combined with estimates of past crustal production, can be used to predict past hydrothermal contributions to the oceans. Consequently the riverine fluxes required to balance past variations in ocean chemistry can be evaluated.

Previous ocean basement drilling efforts have predominantly been focussed in young (<20 Ma) and ancient (> 110 Ma) crust. No holes penetrate greater than 50 m in 45-80 Ma basement, the interval in which the crust is thought to be ‘sealed’ to circulating fluids. Drilling of intermediate age upper crust, preferably along a crustal flow line, would provide essential information on how the crust ages as well as better age resolution for investigations of past seawater chemistry based on crustal alteration.

Coupled microbiological, geochemical, and hydrological studies in ocean crust - alteration, weathering, and long-term CORKed observatories

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Long-term subsurface observatories - in the form of boreholes fitted with CORKs and down-hole instrumentation/samplers - have been proven to provide invaluable hydrogeological, geophysical, and geochemical records of conditions within ocean crust following rebound post-drilling. CORK-ed boreholes can also be used as platforms for investigating the hard-to-access deep subsurface ocean crust biosphere. We have experimentally tested microbial observatories - in the form of passive colonization experiments with different mineral substrates - deployed for four years within CORKed boreholes on the Juan de Fuca ridge flank. Newer flow-through colonization observatories have also been designed and field tested. Our analyses document that the microbial communities which colonize these experiments reflect the in situ biosphere.

New analytical technologies for the deep subseafloor life

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Recent research progress of the deep subseafloor biosphere indicates that the microbial population, activity, and community structures are controlled by the surrounding geophysical and geochemical characteristics as well as by the primary nutrient supplies from the overlying seawater column and/or underlying crustal fluids. The metabolic activity of subseafloor microbes is generally very low corresponding to the nutrient and energy fluxes; hence, most subseafloor microbes are believed to be highly starved or just surviving with minimum life maintenance energy. To understand the nature of these metabolically low life forms in geologic materials, there have been several fundamental problems to be solved; for examples, (1) aseptic sub-sampling of frozen whole round cores, (2) accurate life detection and enumeration, (3) effective and reliable DNA extraction and amplification, and (4) evaluation of low metabolic activities and functioning. We would present here the recent analytical and technological developments and improvements that could address these issues; (1) we deployed a diamond-tipped electric band-saw system in a clean booth, resulting (semi-) aseptic sub-sampling of the frozen whole round core without sample melt, (2) a new method of computer-based fluorescent image analysis has been developed, which device is combined with an automated slide loader robot system for high-throughput analysis, (3) the small extracted DNA is amplified by multiple displacement amplification (MDA) reaction with phi29 polymerase under strictly aseptic experimental conditions, and (4) we used nano-scale secondary ion mass spectrometry (NanoSIMS) to study microbial carbon- and nitrogen-assimilation rates in methane hydrate-bearing deep subseafloor sediments (>200mbsf) off Japan and high pH-borehole fluids (>pH=12.0) in the South Chamorro serpentine seamount. We hope that these analytical and technological developments are useful for the future deep subseafloor biosphere research, including sediment and rock habitats in the ridge systems.

Tuesday 28th July – Evening Key Note Lecture

In Situ Mineral Carbonation in Peridotite and Basalt for CO_2 Capture and Storage

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***In situ* reaction of CO_2 with peridotite to form solid carbonate minerals could be used to capture and store billions of tons of CO_2 per km^3 of rock per year using pure CO_2 as a transport fluid[1]. Mineral carbonation in basalt is likely to be slower[2], but basalts are more abundant near the Earth's surface, and have higher permeability[3,4]. There may be positive feedback regimes in which high reaction rates at high temperature are sustained by exothermic heating, while permeability and reactive surface area are maintained or enhanced by cracking in response to large increases in the solid volume[1]. If so, *in situ* peridotite and basalt carbonation offer a rapid, relatively inexpensive, and essentially permanent method for CO_2 capture and storage. Using surface surface ocean water equilibrated with atmospheric CO_2 as a fluid reactant avoids the cost of CO_2 capture at the source of emission and the cost of CO_2 transport from source to storage site. This is similar to direct "air capture". Reaction rate is predicted to be ~ 50 times slower at 185°C and 300 bars for $P_{CO2} = 0.0004\ P_{total}$ vs $P_{CO2} = P_{total}$ [1].**

Areas where peridotite or permeable basalt are present within a few km of the seafloor (deep enough to stabilize high density, supercritical CO_2 fluid), in shallow water, overlain by an impermeable sedimentary cap, preferably in areas of high heat flow, form ideal sites for IODP studies of present day alteration, permeability, response to elevated fluid pressure (hydrofracture), and perhaps pilot injections of CO_2. IODP offers the ideal platform for this endeavor, leading the worldwide scientific effort in identifying potential sites and in confirming a secure approach for future CO_2 sequestration in sub-sea geologic strata. In the context of IODP planning for the next decade, we propose an international workshop to choose sites for characterization of sub-seafloor CO_2 storage sites, in peridotite, basalt and sediment, and to design experiments to test proposed mechanisms for sub-seafloor CO_2 capture and storage.

- **Natural peridotite carbonation is rapid:** CO_2 uptake by near surface carbonation of mantle peridotite during weathering consumes ~ 10^3 tons per km^3 per year in Oman [1], and mineral carbonation is up to ~ 10^6 times faster at 185°C and 100's of bars P_{CO2} (e.g., 5, 6) yielding potential rates ~ 1 Gt/km^3/year. Natural basalt carbonation is probably slower [2] but, because basalts are very extensive, consumes ~ 10^8 tons CO_2/year globally[7].

- There is a proposed method (patent pending) [1], for **enhanced, natural carbonation of peridotite *in situ*:** (1) Drill peridotite beneath impermeable cap rock, (2) hydrofracture the peridotite, (3) heat rock volume to ~ 185°C at depth using hot H_2O, hot CO_2, flue gas, …, and add $NaHCO_3$ to pore waters to catalyze olivine carbonation, (4) pump CO_2, or H_2O equilibrated with CO_2, at 100-300 bars P_{CO2}. Alternatively, use surface water saturated in atmospheric PCO_2, slower but potentially much less expensive.

- **Rapid carbonation is self-heating:** Mineral carbonation is exothermic, and this can be used to reduce energy costs via reactive "self-heating": For example, once a peridotite volume is above ~ 125°C, the reaction rate is fast enough for heat production to exceed diffusive heat loss to cold surroundings and advective heat loss to cold CO_2-rich fluid pumped at ~ 1 cm/s1.

- **Rapid carbonation may be self-cracking:** Though reactions involving crystallization in pore space could be self-limiting due to armoring of reactive surfaces and dropping permeability [8-16], as observed for hydration and carbonation of basalt [7, 17-19], extensive outcrops of completely carbonated peridotite (listwanite) show that natural carbonation is not always self-limiting e.g., [20, 21]. Listwanites have brecciated textures in outcrop and dense, hierarchical fracture networks extending to microscopic scales, filled by syn-kinematic carbonate and quartz veins, probably due to feedback between volume change, stress increase, and fracturing that maintains permeability and reactive surface area [1]. Hydrothermal systems producing carbonate from peridotite remain active for tens of thousands of years [1, 22]. Experiments on carbonation of porous peridotite showed increasing permeability vs time [23].

- **Added cost compared to "simple" injection of CO_2 into subsurface pore space is small:** (a) hydrofracture cost – one time only, probably negligible per ton of CO_2 consumed – and (b) preheating. To heat 100°C with heat capacity 850 J/kgK requires 85 kJ/kg peridotite. Since complete carbonation involves 0.6 kg CO_2/kg peridotite, this is ~ 140 kJ/kg CO_2 consumed. If heating + carbonation is 20% efficient, this requires ~ 700 kJ/kg. Burning fossil fuel to generate electricity produces 3000 to 8000 kJ/kg CO2. In this case, the energy penalty compared to "simple" injection is ~ 9 to 23%.

- **Enormous storage capacity in peridotite**: The Oman ophiolite is ~ 70,000 km^3 [24]. ~ 30% of this volume is peridotite. Adding 1 wt% CO_2 to this peridotite would consume ¼ of all atmospheric CO_2. Full carbonation of peridotite, forming solid carbonates + quartz, would consume more than 40 wt% CO_2, corresponding to more than 30,000 Gt of CO_2 in the Oman peridotite alone. Similar size ophiolites are in Papua New Guinea (outcrop ~ 10,000 km^2), New Caledonia (~ 6000 km^2) and along the east coast of the Adriatic Sea (several ~ 4000 km^2 massifs). All of these, except perhaps for the Balkan examples, extend offshore beneath marine sediments. This is particularly evident where peridotite outcrops along the shoreline.

- **Basalt carbonation kinetics are uncertain:** Data suggest that carbonation of crystalline basalt is 10 to 100 times slower than peridotite carbonation [2], which is a problem from the point of view of self-heating and reactive cracking but (a) dissolution of basaltic glass may be much faster than dissolution of crystalline basalt [25], and (b) peridotite carbonation rates are highest at high $NaHCO_3$ concentrations [5, 6], while comparable experiments have not been done on basalt.

- **Enormous storage capacity in basalt:** High porosity and permeability in some basaltic lava flows capped by low permeability sediments makes them attractive targets for "conventional" CO_2 storage via injection into pore space[3, 4]. Estimated storage capacities in pore space for deep-sea basalt aquifers overlain by suitable cap rocks include 500-2500 Gt of CO_2 in the Juan de Fuca Ridge region, and 1000-5500 Gt in the Caribbean flood basalt province [3, 4]. Displacement of ambient pore water to the seafloor is far less problematic than displacement of saline fluids from on-land aquifers, and leakage of CO_2 to the seafloor is also less problematic than on land. Compared to clastic sediments, basalt has a much higher capacity for mineral carbonation, so that large masses of CO_2 injected into basalt will eventually be near-permanently stored in solid carbonate minerals. Mineral carbonation in basalt consumes less CO_2 per kg than in peridotite, but the mass of basalt near the seafloor is enormous.

Since 1990, tectonically exposed peridotite and basalt, rich in Mg and Ca, have been considered promising reactants for conversion of atmospheric CO_2 to solid carbonate [26, 27]. However, engineered techniques for *ex situ* mineral carbonation, "at the smokestack", are problematic. Kinetics are slow unless mineral reactants are ground to powder, heat-treated, and held at elevated pressure and temperature (e.g., [5, 28]). Currently, when combined with the cost of CO_2 capture from flue gas, this involves a 60-180 % energy penalty compared to power plants without CCS, though engineering studies continue [29].

It may be more practical to carbonate peridotite and basalt *in situ*, eliminating quarrying, transportation, and grinding, and capitalizing on thick peridotite massifs to reduce diffusive heat loss and maintain fluid pressure [1]. Fyfe [30] proposed that exothermic hydration of olivine to form the mineral serpentine may heat peridotite. "Self-heating" is more efficient via carbonation rather than hydration because reaction rates are faster and carbonation enthalpy per kg is larger than hydration [1]. Once a rock volume is in the self-heating regime at depth, CO_2-rich fluid entering the volume at surface temperature is heated by the exothermic reaction. Inflow rate can be adjusted to maintain high temperature and optimal peridotite carbonation rates [1]. This avoids the cost of maintaining high temperature in a reaction vessel.

Fluid-rock reactions that increase the solid volume are often self-limiting because they fill porosity, reduce permeability, and create "reaction rims" that act as diffusive boundary layers between unreacted mineral reactants and fluid [8-16], as observed for hydration and carbonation of basalt [7, 17-19] However, crystallization in pore space can also fracture rocks and increase permeability, especially for salts crystallizing from water in limestone and other building materials [31, 32] and the similar process of frost cracking [33]. MacDonald & Fyfe [34] proposed that increasing solid volume associated with olivine hydration (serpentinization) produces stresses that fracture surrounding rock, as further investigated for serpentinization (e.g., [35, 36-39]) and granite weathering [40]. Reactive cracking may be likely during rapid mineral carbonation, and unlikely during slow carbonation, because increasing stress due to carbonate precipitation in pore space competes with relaxation mechanisms such as viscous deformation of carbonate minerals [41]. This is consistent with experiments on crystallization of low viscosity [42] Na-sulfate salts in porous limestone: Rapid crystallization caused fractures, while slow crystallization did not [43]. If a rock volume enters this self-cracking regime, this avoids the cost of repeated hydrofracture for *in situ* carbonation, and the cost of grinding solid reactants for *ex situ* carbonation.

Compared to injection of supercritical CO_2 into pore space, the added costs for *in situ* peridotite or basalt carbonation (preheating and/or hydrofracting a rock volume at depth) could be small, particularly if the procedure is done in an area with high heat flow where subsurface peridotite or basalt is already hot, and thermal convection can drive fluid circulation. Furthermore, if surface water saturated in atmospheric P_{CO2} is used as a fluid reactant, the proposed process can be used for "negative CO_2 emissions", similar to air capture and unlike CO_2 capture at power plants and other sources. However, the rate enhancement due to temperature and pressure is ~ 50 to 100 times smaller if sea water rather than CO_2-rich fluid is used as a reactant, so the rate of exothermic heating (and reactive cracking?) is correspondingly reduced [1].

It is crucial to gather information on existing alteration, fracture density, stress state, porosity and permeability in near-seafloor peridotite and basalt, overlain by a sedimentary cap rock, and to explore hydrofracture and CO_2 injection experiments. Offshore targets are plentiful, and there are many synergy between this research and work on igneous accretion of oceanic crust, alteration and deformation of the crust, ocean history, hydrology and biogeochemistry. In the context of IODP planning, we propose an international workshop to choose the best sites for such studies, and to design experiments to test proposed methods for sub-seafloor CO_2 capture and storage. The scope of the workshop should probably include storage in sedimentary formations, as well as peridotite and basalt. In addition to site identification and experimental design, workshop discussions could include current and future potential for modeling of reactive porous flow, hydrofracture (intentional, to enhance permeability, and unintentional, leading to potentially rapid CO_2 leakage), potential environmental impact, and potential for biogeochemical enhancement of mineral carbonation. IODP effort on this topic is worthwhile and timely because of the potential for permanent, sub-seafloor storage of immense amounts of CO_2.

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Abstracts for short talks on Advances in Mid-Ocean Ridge Science and Deep Drilling Technologies

(in order of presentation)

The *Chikyu* Enhancement Plan - Road to the Mantle

Masaoki Yamao, Yoshio Isozaki & Shin'ichi Kuramoto
(CDEX, JAMSTEC)

The Center for Deep Earth Exploration (CDEX) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is an implementing organization of IODP and operates *D/V Chikyu,* a state-of-the-art scientific drilling vessel. Since delivery in July 2005, *Chikyu* has been drilling riser and riserless wells off Japan (Shimokita and Nankai) and overseas (Kenya and Australia) for the last 4 years. While these wells have demonstrated the high performance of *Chikyu's* drilling capabilities, currently the maximum operational water depth is limited to about 2,500 m due to technical limits of the riser joints and the Blow Out Preventer (BOP). JAMSTEC/CDEX has been working on enhancing *Chikyu's* systems to meet future scientific requirements, i.e. to reach the Earth's Mantle by drilling in water beyond 4,000 m deep and to a total drilling depth of 12,000 m.

1. Overall Development Target

	Current Spec	Target Spec
Maximum Operation Water Depth	2,500 m (Riser)	4,000 m+ (Riser/Riserless Mud recovery)
Total Drilling Depth	10,000 m	12,000 m
Bottom Hole Temperature	150 ºC	300 ºC
Personnel on Board	150	200

2. Target-reaching Technology Development

A. Deep Drilling Technology
- Ultra-Deep Drill Pipe: High Tensile Steel
- High Temperature: Seal to be used under 300 ºC, High Temperature Drilling Mud
- Ultra-Deep Casing Pipe: Expandable Casing

B. Deep Coring Technology
- MWC Tool: Measurement While Coring
- MDCB: Motor Driven Core Barrel
- Core Bit: 8-1/2" OD, PDC & Implemented Diamond Bit

C. Ultra Deep Water Technology
- Riser System: Buoyant Riser constructed of Lightweight material (Aluminum/Titanium/CFRP etc.)
- RMR System: Riserless Mud Recovery w/Submarine Pump
- High Current: Anti-VIV (Vortex Induced Vibration) Riser Fairing
- BOP System: Ultra-High Pressure BOP (more than 20000 psi WP) & Control

Chikyu is now conducting NanTroSEIZE riser drilling operations off Kumano. Data on such operations and variables as: vibration effects on riser performance, riser fairing performance, mud circulation and treatment capability are being collected as operations proceed.

Engineering to Support Transformative Science: Ultra-deep drilling in Hyper-Deepwater

Greg Myers
(IODP-MI)

The effort to achieve transformative science in scientific ocean drilling is extremely challenging due to the fact that we are often drilling and coring in environments beyond the reach of available technology. Yet to achieve our ambitious science goals, IODP must make technological leaps, where off the-shelf-solutions do not exist, especially in areas of drill string stabilization and borehole pressure management for ultra-deep holes in water depths greater than 12,000ft (hyper-deepwater, >3500 m). In addition to these substantial technology efforts, many ancillary improvements must be made in materials, operational techniques and project management. Technological solutions are presently emerging to these challenges and these will be discussed during this talk.

Implications for mid-ocean ridge hydrothermal and magmatic processes from microearthquake data at 9°50'N East Pacific Rise

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An array of up to twelve Ocean Bottom Seismometers (OBSs) was deployed at 9°50'N along the East Pacific Rise from October 2003 through January 2007. The rate of microearthquake activity steadily increased from the start of the first deployment leading to a seismic crisis on January 22nd 2006, interpreted as an eruptive diking event (Tolstoy et al., 2006). This steady increase in seismic activity followed by an abrupt drop in activity after January 22nd 2006 suggests that the earthquakes are dominately caused by the build up in extensional tectonic stresses following the previous diking event (Haymon et al., 1993, Rubin et al., 1994). Analysis of microearthquakes from the first deployment (October 2003-April 2004) has shown that seismicity is tightly clustered along the axis (Tolstoy et al., 2008). A vertical pipe of seismicity associated with a small kink in the axial summit trough is interpreted as a zone of on-axis hydrothermal recharge, with hydrothermal flow moving predominantly along-axis rather than across-axis as has often previously been inferred. This mode of narrowly concentrated along-axis flow is supported by in situ temperature measurements as well as by tidal triggering of earthquakes which show a pattern of propagation with diffusion of the tidal pressure wave (Stroup et al., in review). Because permeability is essential to hydrothermal circulation, tectonic stresses that create and maintain networks of cracks may be the dominant control on the architecture of hydrothermal circulation. Concentrated tip-stresses associated with small kinks in the axis may act as drivers for the location of hydrothermal recharge in the fast spreading environment.

This project is being done in collaboration with Felix Waldhauser (LDEO). Others who contributed significantly to the results include: Robert Weekly (now at UW), Lindsey Doermann (LDEO), Del Bohnenstiel (NCSU), Danielle Stroup (LDEO), Tim Crone (LDEO), Alberto Malinverno (LDEO) and Won-Young Kim (LDEO).

Core reorientation at Atlantis Massif using Formation MicroScanner imagery

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Palaeomagnetic remanence directions are routinely used as markers for tectonic rotation in a variety of tectonic settings. In ODP and IODP hard rock core materials, however, their utility is restricted by the lack of azimuthal control on the orientation of core samples. Individual core pieces are free to rotate within the core barrel, effectively randomising remanence declinations and allowing only the inclination of the magnetic vector to be used in tectonic analyses. In these circumstances, tectonic rotation may be inferred from differences between observed and reference inclinations, but the amount of rotation and the orientation of the rotation axis cannot be constrained directly. In fact, an infinite number of rotation axes and associated rotation angles exist that are capable of restoring an observed inclination to its pre-rotation value, such that specification of a rotation angle requires the orientation of the rotation axis to be assumed a priori. Conversely, inclinations that are identical to the reference value cannot be used to exclude the potential for tectonic rotation, since in the absence of declination data an infinite number of rotation trajectories may be found that initially steepen the remanence inclination but then restore it to its initial value.

In order to provide robust, quantitative constraints on tectonic rotation parameters it is necessary to obtain fully oriented palaeomagnetic data (i.e. both remanence declination and inclination). Unfortunately, current IODP hard rock drilling technologies do not permit collection of fully oriented drill core samples. Here we demonstrate the viability of an alternative approach involving reorientation of samples by comparing structures determined on individual core pieces with oriented microresistivity images of the borehole wall obtained using the Formation MicroScanner (FMS) tool. We apply this core re-orientation technique to palaeomagnetic data from IODP Expedition 304/305, which sampled exhumed lower oceanic crust at Atlantis Massif, an oceanic core complex located on the western flank of the Mid Atlantic Ridge at 30°N. Hole U1309D reached a total depth of 1415 metres below sea floor (mbsf), had a high average core recovery of 74% and high resolution FMS images. By re-orienting structural features seen on core pieces sampled for palaeomagnetic analyses in the upper 400 mbsf, the associated remanence directions may be restored to true geographic co-ordinates. Results demonstrate a 46°± 6° counterclockwise bulk rotation of the Atlantis Massif footwall around a Mid-Atlantic ridge-parallel horizontal axis trending 011°± 6°, consistent with rolling-hinge models for the development of oceanic core complexes. In addition, palaeomagnetic data from the upper 180 metres of the footwall section demonstrate the dangers of simplistic interpretation of IODP inclination data. This interval has a mean inclination indistinguishable from the reference value, but reoriented data conclusively prove that this section has also rotated substantially.

Future research at this site will involve using our core-log reorientation methodology to investigate the detailed structure and variation in rotational strain *within* the Atlantis Massif detachment fault footwall. This will require increasing the sampling density of reoriented core pieces and application of a rigorous technique for quantifying tectonic rotation that integrates palaeomagnetic data with structural constraints derived from reoriented kinematic indicators.

Lava Deposition History in ODP Hole 1256D: Insights from Log-based Volcanostratigraphy

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Detailed, high-resolution volcanic stratigraphy of Ocean Drilling Program (ODP) Hole 1256D, built on the integration of downhole wire-line logs and core data, made it possible to provide the fine-scale vertical cross-sectional view of the *in situ* East Pacific Rise (EPR) upper crust. The model is mainly based on ten electrofacies identified from high-resolution Formation MicroScanner (FMS) images. The electrofacies within extrusive rocks are correlated with commonly observed EPR lava flow types, such as sheet flows and breccias, and subordinate pillows. Combining with well-studied EPR surface geology, this stratigraphy model sheds a new light on *in situ* EPR upper oceanic crust construction processes that have been detected only indirectly from subsurface geophysical data. In particular, the formation of a ~100 m of pillow section observed in Hole 1256D could constraint the lava deposition history in the superfast spreading crust.

We introduce the first realization of detailed upper crustal architecture and construction process represented by logging data in Hole 1256D. We used Shinkai6500 dive data from southern EPR (14° S) to obtain both special and time reference frames for modelling lava deposition history in Hole 1256D. Using these reference frames and assuming paleo spreading rate was constant, 50 % of the extrusive rocks in Hole 1256D crust was formed within ~2 km of the ridge axis whereas nearly all of the rest of extrusive section was formed within ~3 km of the ridge axis. These results are consistent to the upper crustal construction rate suggested by seismic studies.

Maximizing the value of existing crustal holes by reentry from IODP drillships or oceanographic vessels

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While defining optimal new ocean crustal drilling targets may be a primary objective of this workshop, limitations on IODP resources (not just at present but potentially post-2013) suggest a complementary strategy of maximizing use of existing crustal reentry holes. Utilizing existing holes avoids expenses associated with starting new holes, and in some cases could take advantage of short segments (less than the traditional leg) of drilling platform time that might come available in the scheduling process. Such options can also be useful as potential contingencies in case of drilling problems at nearby primary targets. There are several good past examples of multiple revisits to important DSDP/ODP crustal reentry holes using the *Glomar Challenger* and *JOIDES Resolution* and also US and French wireline or submersible based reentry capabilities. Objectives have included deeper drilling, advanced logging, special experiments, and installation of observatories. (hydrological and seismological). More recently, capabilities have expanded to allow installation of observatories and exchange of observatory instrument strings using deep submergence assets.

Some highlights of reentry activities to date include:

- deepening of important crustal holes (e.g., 504B through 1993, 1256D at present)
- advanced logging programs and special experiments (e.g., 395A, 418A, 504B)
- hydrological and seismic observatories in old holes (e.g., 395A and 396B)
- true video logging of ocean crust by wireline reentry (896A)
- installation of observatories by wireline reentry (e.g., 504B and 896A).

The status of existing ocean crustal reentry holes will be briefly reviewed and some prime opportunities for future reuse will be highlighted. The latter include installation of microbiologically-focused observatories, e.g., as is planned for Hole 395A as will be described by K. Edwards on 27 July or could be proposed for other prime opportunities like Hole 896A that produces warm basement fluids. There are a few existing crustal reentry holes in good condition that could be deepened if there is scientific interest. If/when drilling limits are reached in Hole 1256D, what is the best subsequent use of that hole? Another potential coring approach has been discussed for many years but not actually implemented – sidewall coring of important intervals in existing holes. Future opportunities might also include greater utilization of several good reentry holes intended for ocean seismic network observatories that have not been implemented for various reasons. Finally, there are completely novel potential uses of existing crustal holes such as in CO_2 sequestration, as was once proposed in ODP and will be discussed in greater detail by P. Kelemen in the 28 July evening keynote lecture.

Metasomatic mass transfers in heterogeneous ocean crust: New insights from recent basement drilling expeditions

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Heterogeneous crust is accreted along much of the length of slow-spreading ridges. Unlike layer-cake crust with fairly uniform basaltic composition, heterogenous crust has varied lithologies, ranging from peridotite to troctolitic and gabbroic to felsic rocks, often on small spatial scales. Recent studies, mainly of rocks from Legs 209 and 304/305, have led to new insights into the fundamental processes governing alteration of heterogeneous crust. It turns out that the lithological variability has profound implications for metasomatism, because diffusional mass transfer is strongly promoted in cases where lithologies with significantly different chemical potentials of major rock components are juxtaposed against each other. Many of the features characterizing the metamorphic petrology of rocks from heterogeneous crust at different spatial scales can be explained by relating these chemical potential differences to intensities of fluid-rock interactions and related mass transfer.

These insights have also led to a fresh look at alteration of peridotite, as silica transfer during serpentinization appears to be a dominant process. The combined hydration of olivine to serpentine and brucite on the one hand and of orthopyroxene to serpentine and talc generates tremendous drive for reaction and for diffusional mass transfer. The system is highly reactive, because the difference in chemical potentials of silica between the serpentine-brucite and serpentine-talc buffers in the two reaction centers is great (~ 2 orders of magnitude). In peridotites with <43% opx, the thermodynamic drive is high until talc is completely reacted away. This leads to highest possible (far-from-equilibrium) reaction rates throughout much of the history of serpentinization, which in turn leads to a permeability increase (not sealing) during serpentinization. These relationships explain why serpentinization is always pervasive, while alteration of gabbros is not. If, however, gabbros are in contact with peridotites, alteration is extreme and mass transfers are great. The result is either rodingite or chlorite blackwall. The nature of the secondary mineralogy of the gabbro depends on the temperature-dependent phase relations in the peridotite-fluid system. At temperatures below ~330°C, the intergranular fluid within the serpeninite is buffered by diopside-brucite-serpentine, making it alkaline with a very low activity of aqueous silica. These fluids will turn a gabbroic dike into rodingite. At 400°C, the serpentine-talc-tremolite assemblage buffers the intergranular fluid in peridotite to moderate silica activities and pH and the gabbro at the contact is predicted to yield to chlorite±(talc-tremolite). If ultramafics dominate in a parcel of retrograded heterogeneous crust, one would expect to find serpentinite and rodingite. Where gabbroic intrusions prevail, most of the intergranular fluids will be near quartz-saturation. When those fluids encounter serpentinite, brucite will react to serpentine and eventually serpentine will react to talc. This can explain the talc schist in many detachment faults and the steatitization of serpentinites in hydrothermal upflow zones.

It took deep drill cores to figure this out, because one of the key phases – brucite – is dissolved away in serpentinites exposed at the seafloor.

Posters Abstracts and White Papers

(Alphabetical Order of 1st Author’s Name)

Confess our discontinuity:
Heading to the breakthrough and the feasible Mohole

Natsue ABE
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The oceanic plate is the upper thermal boundary layer and plays an important role to transport heat and substances from and into the deep Earth to the surface. We have to know the formation and evolution of the oceanic lithosphere in order to estimate of the heat and the material flow accurately. In order to understand the evolution of the oceanic lithosphere, we need to know both of the vertical structure and horizontal developments together.

The formation of the oceanic crust is the first differentiation process from the earth's mantle to the Earth's surface and it must be the main processes during oceanic plate formation. On the other hand, the crust-mantle boundary, Mohorovicic seismic discontinuity, is the important factor to estimate total volume of the Earth's crust. It is the shallowest discontinuity that we will be able to touch directory in the near future. There are several seismic discontinuities inside of the Earth's interior and "the Moho" is the boundary that shows the most drastic change of their physical properties between their and shallowest discontinuity of them. Despite the shallow depth, our human being has not touched the in situ mantle, yet. Our scopes on these boundaries have just touched to the layer2a and 2b boundary.

Soon, we are going to have a great tool, "CHIKYU", to drill through "Moho" and get to the mantle. Even if it is not enough to understand whole system of the Earth Interior, the very first insight into the intact lower crust and the untouched mantle has important implications for the whole earth system. This is the rare opportunity to accomplish Mohole drilling for the first time in this half century. It will be definitely a breakthrough of the Earth Sciences. I would like to propose a step wise plan to understand the oceanic plate and the feasible Mohole project.

Beyond hotspots: the importance of rift history for volcanic margin formation

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Jenny Collier (ICL) and Tim Minshull (NOCS)

Ocean basins form from the breakup of continents. Continental breakup is accompanied by highly variable amounts of magmatism. At some margins massive outpourings of igneous material occurs, whilst at others there is almost none. Based on detailed observations of the North Atlantic, the paradigm that the degree of magmatism is controlled by mantle temperature has dominated our understanding. However recent observations from the Northwest Indian Ocean, where breakup is unequivocally linked to onshore flood basalts, the Deccan Traps, and a hot spot track leading to Reunion Island, found that the Seychelles – Laxmi Ridge continental margins have little evidence of magmatism. From the application of a new dynamic model for the evolution of the North Atlantic and northwest Indian Ocean, we present a new understanding of rift margins: the volume of rift-related magmatism observed depends not only on the mantle temperature but equally on previous rift history. The association of flood basalts with the volcanic nature of the North Atlantic margins has led to an over-emphasis on the thermal structure to explain melt volumes during continental breakup. The interactions are individual to each margin. In the North Atlantic, extension prior to rifting focused upwelling and so enhanced melt generation. In the northwest Indian Ocean, prior extension exhausted the mantle thermal anomaly associated with the Deccan Traps, leading to reduced melt generation. Our work has therefore shown that the explicit inclusion of prior rift history is needed in order to fully understand the timing and volume of magmatism observed during continental breakup.

Seismic velocity structure of the subducting Pacific lithosphere around the axial part of the Japan trench by wide-angle seismic experiment: Change of Vp and Vp/Vs caused by development of bending normal faults

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We conducted an airgun-OBS wide-angle seismic experiment along two seismic lines: one is along the outer rise and another along the inner trench areas of the Japan Trench subduction zone. In the obtained seismic structure model, we found that the Vp and Vp/Vs ratio of the oceanic crust and upper mantle near the Japan Trench are significantly different from those estimated in the Northwestern Pacific Basin [Shinohara et al., 2008], where typical oceanic crustal structure exhibited. Substantial amount of reduction in Vp was observed in the crustal layers around the Japan trench. Similar observations have been reported in the middle to southern American subduction zone, where the normal faulting caused by lithospheric bending near the trench is considered to be responsible for the Vp reduction. Vp/Vs was also estimated for the crustal layer and turned out to be larger than the value estimated in the NW Pacific Basin, implying increase of cracks density. Whereas, the Vp/Vs ratio of the upper mantle does not show evident difference from the observation at the NW Pacific Basin. These results may indicate that bending related deformation is large enough to alter the seismic velocity in the oceanic crust but not enough to cause hydration reaction in the mantle.

Geophysical Signatures of Oceanic Core Complexes: Focus on Atlantis Massif, MAR 30°N

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Oceanic core complexes expose intrusive mafic rocks and at least lenses of mantle ultramafic rock via long-lived detachment faulting within the axial zone of a spreading center. While seafloor mapping over the past decade has significantly advanced understanding of the global distribution and surface geology of OCCs, firm constraints on subsurface structure are still quite limited. Recent conceptual and numerical models predict that mafic intrusions and at least a modest level of magmatic activity are important factors in OCC evolution. In order to test these models, the distribution of mafic rock within the lithosphere and, ideally, measures of crustal thickness variability are required. The existing seismic data at Atlantis Massif on the Mid-Atlantic Ridge, 30°N, are sufficient to document fairly detailed (several 10's m vertical resolution) structure within the upper ~1.5 km and broader scale (few-hundred meters vertical resolution) structure to lithospheric depths of 4-7 km. By combining MCS and OBS refraction data, we are in the process of obtaining a velocity model along a grid of lines that cover each structural component of this OCC.

Our recently-published seismic velocity model for the Central Dome of Atlantis Massif is consistent with the full suite of geological and geophysical data; all of thesedata show that mafic intrusive rocks dominate the upper portion of the footwall of this oceanic core complex and that laterally extensive zones of ultramafic rocks are not required by the data. The origin of subseafloor reflectivity beneath the central dome has not yet been determined in detail but results to date indicate that downhole variations in alteration give rise to reflections observed within the upper kilometer of the central dome. Our eventual tomographic results for broader region will allow us to assess the extent and continuity of velocity anomalies which may be indicative of mafic intrusive bodies. Additional goals are to characterize the transition between these bodies and crust that has normal velocity-depth properties, and to compare the signature of the domal core of the OCC to that of the adjacent hanging wall and conjugate outside corner crust.

Advanced Seismic Imaging of Oceanic Core Complexes

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Oceanic lithosphere formed along slow- and ultra-slow spreading centers is highly heterogeneous at many different scales. This compositional and structural heterogeneity arises from temporal and spatial variations in mantle composition and thermal structure, magma supply, efficiency of melt extraction, tectonic extension, or a combination of any of these factors. This heterogeneity is well exposed at oceanic core complexes (OCCs), which are deep sections of the oceanic lithosphere exhumed to the seafloor by long-lived detachment faults. Deep drilling at OCCs thus offers a unique opportunity to sample the lower crust and upper mantle of slow-spreading lithosphere. However, the importance of the geological processes inferred from the one-dimensional view that deep drilling provides can only be assessed by understanding the complex, three-dimensional structure of OCCs. Seismic reflection and refraction are powerful methods to image the deep structure of OCCs at several scales and depths. Here we present advances made during the last two years on seismic imaging of OCCs along the flanks of the Mid-Atlantic Ridge. Travel-time tomography of long-offset (6 km) multichannel seismic data reveals the heterogeneity of the shallow (<1.5 km) structure of OCCs at scales of a few to tens of kilometers, while waveform tomography has the potential to image the internal structure of OCCs at scales comparable to those of seafloor observations.

Hydrothermal Fluid Flow in Oceanic Gabbros, IODP Site 1309, Mid-Atlantic Ridge: Strontium and Oxygen Isotopic Composition.

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IODP Hole U1309D was drilled to 1400 mbsf in the footwall of the Atlantis Massif detachment fault at the Mid-Atlantic Ridge 30°N. The core is composed of gabbroic rocks interlayered with olivine rich troctolites and ultramafic rocks, with several basalt/diabase sills in the top 130 m. The dominant alteration occurred in the greenschist facies, at depths at least 1 km below seafloor, and decreases in intensity downhole. Whole rock oxygen isotope values range from +5.5 ‰ to +1.5 ‰, indicating variable degrees of interaction with seawater at temperatures generally > 250°C. Gabbroic rocks and diabases exhibit a range of Sr isotope ratios from MORB values (0.70261) to intermediate ratios (0.70429), while four serpentinite samples from < 400 mbsf show much higher values (0.70687 to 0.70904) close to seawater composition (0.70916). A key question is how fluid with a seawater isotopic signature passed through partially altered gabbros to reach thin ultramafic horizons.

Samples of individual minerals and alteration zones have been extracted from thin sections using a microscope-mounted drill for strontium analyses and have been reduced to powder using a dentist drill for oxygen analyses. In gabbroic samples, igneous plagioclase and pyroxene have MORB-like values. Actinolite replacing pyroxene is generally very low in strontium but can have $^{87}Sr/^{86}Sr$ ratios significantly higher than the whole rock. Secondary plagioclase is isotopically close to the whole rock and alteration occurs between 250 and 350°C according to calibration curves calculated in Zheng (1993). Values close to seawater have been found in vug-filling actinolite veins precipitating at rather low temperature (100-160°C), although bleached feldspar in vein margins is much less radiogenic. These data suggest that fluid percolating through the gabbros was significantly more radiogenic in strontium than the whole rock analyses might suggest. Where fluid flowed through high flux pathways with little exchange with wall rocks, minerals isotopically similar to seawater were precipitated. Serpentinite layers were altered either by fluid passing along such high flux pathways, or at significantly lower temperatures (200-250°C) than the gabbros, as the estimations from the oxygen data show.

Mapping of Seismic Layer 2A at Intermediate-Spreading and Fast-Spreading Crust Exposed near the Blanco Transform Fault and Hess Deep Rift

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We present results from seismic surveys over intermediate-spreading and fast-spreading crust adjacent to the Blanco Transform Fault (BTF) and Hess Deep Rift (HDR) using a source array optimized to image the layer 2A boundary. The imaged layer 2A event is similar in visual appearance and physical properties at the two sites. The mean layer 2A two-way travel time is 370±100 ms and 360±95 ms at BTF and HDR, respectively. Travel-time modeling indicates an average layer 2A velocity of 2.65 km/s at these study areas, which results in layer 2A thicknesses of 485±135 m at BTF and 475±125 m at HDR. These values are similar to published layer 2A measurements of slow-spreading, intermediate-spreading, and fast-spreading young oceanic crust.

At both BTF and HDR several regions are observed where layer 2A is consistently thin or thick. These regions are ~2.5-10 km wide in a ridge-parallel (isochron) direction, corresponding to 100-333 Ma and 40-125 Ma of spreading at BTF and HDR, respectively. The regions can extend 15 km or further in the flowline direction. There is no correlation between layer 2A thickness and seafloor bathymetry.

Drillhole and tectonic window observations suggest that lava thicknesses vary on a much greater scale than observed seismic layer 2A thicknesses, and that there is not a universal correlation between seismic and lithologic boundaries. In our study areas the layer 2A/2B boundary is imaged near the top of the sheeted dike complex at HDR, but is imaged significantly above the sheeted dike section at BTF. There may be a crack thickness threshold near 400-600 m depth at which cracks are easily sealed with alteration products which results in the layer 2A/2B boundary generally falling within this depth range. Additional drilling in young oceanic crust through the 400-600 m depth interval is required to ground truth the nature of the layer 2A/2B boundary.

Depth-shifting and orientation of core data using a core-log integration approach: a case study from ODP-IODP Hole 1256D

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Core recovery in oceanic context is generally not equal to the total depth of the coring interval and this can result in depth uncertainties for the recovered material. In hard rock environments, the difference between cored depth and core recovery depends on several factors associated with drilling operations. The main factors are typically (1) core disruption during perforation; (2) ship's dynamics while drilling in variable sea states; (3) rock fragments that fall off the borehole wall to the bottom of the hole; and (4) rock pieces that remain inside the core barrel and are not retrieved until the subsequent core barrel is recovered. Besides depth ambiguity, cores recovered using rotary core barrel drilling techniques are not oriented with respect to North. We present a new methodology for depth shifting and reorientation of core data using a core-log integration approach that enables to relocate each core piece to the appropriate in situ depth and also to reorient core structures to magnetic North. This method uses a direct correlation of core measurements to downhole high-resolution resistivity Formation MicroScanner (FMS) and acoustic Ultrasonic Borehole Imager (UBI) measurements. We used this technique on data from the "Lava Pond" unit, which is the shallowest portion of ODP-IODP Hole 1256D (6° 44.2'N, 91° 56.1'W). The Lava Pond unit has a high core recovery percentage (93%) that allows for reliable correlations between downhole logging and core data. Using our technique we first reduced the depth shifting errors due to core recovery (R%) ≠ 100% by identifying new depth intervals for each core piece and use these results to focus on the core-log correlations. We then used a MATLAB script for implementing a mathematical procedure to create "*structural images*" from core data in a fashion similar to those obtained from FMS and UBI images. Finally, we correlated the "*structural images*" to interpreted FMS and UBI images using only core pieces that were long enough to assure having vertical alignment reference. A total of 106 core pieces out of 142 (67.72 m over 68.57 m recovered) were ultimately used and approximately 80% of the core pieces were oriented and depth shifted. Overall, a total of 598 structures in the ~74 m-thick Lava Pond unit were identified and 544 structures were re-oriented and depth shifted. The core-log integration approach using the methodology described here provides the means to match a high percentage of core pieces to downhole logging data and produced a very reliable correlation. "*Structural images*" being characteristic and unique patterns for each core piece, provide diagnostic information for a distinctive correlation between log and core data.

Effects of Plate Boundary Geometry on Azores/Terceira Rift Magmatism: Constraints from Bathymetry, Gravity, and Numerical Modeling

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Plate boundary geometry can affect the spatial distribution and volume of magmatism occurring along a mid-ocean ridge. The Azores Plateau is located in a relatively complex geological setting which includes a triple junction, ridge obliquity, an ultra-slow spreading ridge, zones of diffuse seafloor spreading within ~100 km of the triple junction point (rather than linear accretion focused along a spreading center; e.g. Searle, EPSL 1980), a major fracture zone, and a postulated hotspot. The precise nature of the Azores hotspot is somewhat debated, as several lines of evidence (e.g., absence of age progression along islands, apparent lack of an organized tomographic anomaly in several seismology studies) suggest that the hotspot may not follow the classic deep-seated plume model. Thus, this study uses a finite element numerical model to assess how selected aspects of plate boundary geometry affect mantle temperature, mantle velocity, and crustal production in a triple junction with kinematic similarity to the Azores Triple Junction. The numerical model (Georgen, EPSL 2008) incorporates pressure- and temperature-dependent viscosity as well as thermal buoyancy, and flow within the model is driven by both thermal gradients as well as surface plate motion away from a fixed triple junction point. The model focuses on the slowest-spreading (half-rate approximately 0.3 cm/yr) ridge of the Azores Triple Junction, the Terceira Rift, along which much of the subaerial volcanism in the plateau is roughly aligned. The effect of varying ridge obliquity observed along the Terceira Rift is also assessed using an independent melting model (Cannat et al. AGU Geophys. Monogr. 2004). In general, the presence of a long fracture zone (similar to the Gloria FZ bounding the eastern end of the Terceira Rift) is found to have little effect on mantle temperature and velocity for along-axis distances <300 km from the triple junction, although crustal production is predicted to diminish to zero within approximately 150 km of the simulated fracture zone. Varying obliquity accounts for differences of <2 km in melt thickness in the 1-D melting model, and up to ~3 km of melt thickness variability in the context of the more complex 3-D thermal and flow field of the triple junction. The use of a linear axis makes it difficult to assess the importance of additional segment-scale melt focusing due to ridge obliquity (e.g., Magde and Sparks, JGR 1997; Dick et al. 2003). When several ridge geometrical effects are combined (i.e., a triple junction and a zone of diffuse deformation within ~100 km of the triple junction point), ~2.5 km of variability in crustal thickness is predicted for the slowest-spreading ridge, roughly 25% of the 10-12 km of crustal thickness suggested for the Azores Plateau based on seismological and gravity data. These numerical experiments suggest that while plate boundary geometry effects may play an important role in crustal accretion in the Azores region, additional factors such as a hotspot or variable mantle source geochemistry are likely required to explain the full scale of the observed magmatism.

Effects of Plate Boundary Geometry and Kinematics on Mantle Melting Beneath the Back-arc Spreading Centers along the Lau Basin

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The back-arc spreading centers that extend along the Lau Basin exhibit trends in axial morphology, crustal thickness, and geochemistry, which are opposite those typically observed at mid ocean spreading centers. We develop 2D numerical models of mantle flow, thermal structure and melting of the Lau back-arc-Tonga subduction system to determine whether along-strike variability in the circulation pattern within the mantle wedge or the extent or rate of slab devolatilization could explain the trends observed. We use present day plate and subducted slab geometries and velocities to explore a range of mantle potential temperature and water content scenarios and test if predictions could match observations of crustal thickness and water content of the magmas erupted at the spreading ridges. We simulate kinematic conditions, including proximity of the trench/arc and rate of slab subduction, for each of three Lau spreading centers–Valu Fa Ridge, the Eastern Lau, and the Central Lau.

Within the range of mantle parameters tested, we find that a potential temperature of 1300 °C and source water contents of > 0.15 % wt are required to match observed crustal thickness and magma water contents at Valu Fa. Substantially less water in the mantle source is required to match the Eastern Lau and Central Lau observations at the same or higher mantle potential temperatures. We predict that the arc and back-arc melting regions are interconnected for all temperatures and water contents at the Eastern Lau spreading center and at Valu Fa Ridge, while at the Central Lau they are only connected for cases when mantle potential temperature is 1400 °C or greater. We hypothesize that the longer-lived Eastern Lau and Central Lau rifting and axial volcanism may have dehydrated the mantle wedge and slowed melt production beneath these spreading centers. The Valu Fa Ridge, which is actively propagating into more hydrated wedge associated with the Tofua arc, experiences enhanced melting relative to the other two spreading centers.

Although wet melting is required in our models to explain the observations, dry melting is found to produce the greatest crustal thickness at the slowest spreading rate, which is observed at Valu Fa Ridge. In this case, fast subduction in combination with the proximity of the trench and spreading center results in enhanced upwelling and, therefore, increased crustal production. If subduction rate were constant at 45 mm/yr, a dry, 1350 °C mantle potential temperature model predicts that the crustal thickness at the Central Lau and Valu Fa would be within 0.1 km. In contrast, for present day kinematics, our models predict the crustal thickness at Valu Fa to be 3.1 km thicker than Central Lau, much closer to the observed values.

Hydrothermal alteration of fast spread ocean crust: Insights from ODP Site 1256

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Drilling at ODP Site 1256 recovered the first intact section of upper oceanic crust. Detailed sampling through the core has produced high-resolution whole rock δ^{18}O and ^{87}Sr/^{86}Sr isotopic profiles to investigate down-hole variation in hydrothermal alteration.

The δ^{18}O profiles records the downward transition from low temperature alteration with higher δ^{18}O values (5.6-11.6‰) in the volcanics to high temperature alteration in the sheeted dikes and plutonic section (2.2-6‰). The highest δ^{18}O in the volcanics are associated with altered glass, halos and alteration focussed around vesicular patches.

The whole rock ^{87}Sr/^{86}Sr profile exhibits crustal scale variation in ^{87}Sr/^{86}Sr from fresh Site 1256 MORB. Generally the uppermost crust (on and off axis volcanism) has exchanged limited strontium with seawater-derived fluids (average ^{87}Sr/^{86}Sr for the lava pond, inflated flows and sheet and massive flow are 0.7033, 0.7032 and 0.7032 respectively). Beneath the volcanics ^{87}Sr/^{86}Sr values are shifted towards seawater values. The upper 200m of the sheeted dike complex records the most pervasive shifts in ^{87}Sr/^{86}Sr with a progressive range of ^{87}Sr/^{86}Sr ratios towards hydrothermal fluid values (0.7051 to 0.7053).

The dike gabbro-boundary and underlying gabbro contacts record sharp increases in ^{87}Sr/^{86}Sr (0.70507 maximum) whereas the central sections of the units have limited values similar to the volcanics. Detailed sampling across these contacts reveals that fluids were focussed along these contacts with basaltic Sr exchanged approximately 15% more along these contacts than in the central portions of the gabbros.

Focussed fluid flow is also recorded on a millimetre scale in the isotopic signatures along dike margins, where ^{87}Sr/^{86}Sr values are elevated to values approaching hydrothermal fluids and have exchanged up to 25% more basaltic Sr for seawater Sr than the adjacent dike. The dike margins are also associated with lower δ^{18}O values.

Mission Moho: Rationale for drilling deep through the ocean crust into the upper mantle

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Sampling a complete section of the ocean crust to the Moho was the original inspiration for scientific ocean drilling, and remains the main goal of the 21st Century Mohole Initiative in the IODP Science Plan. Fundamental questions about the composition, structure, and geophysical characteristics of the ocean lithosphere, and about the magnitude of chemical exchanges between the mantle, crust and oceans remain unresolved due to the absence of in-situ samples and measurements. The geological nature of the Mohorovičić discontinuity itself remains poorly constrained.

"Mission Moho" is a proposal that was submitted to IODP in April 2007, with the ambition to drill completely through intact oceanic crust formed at a fast spreading rate, across the Moho and into the uppermost mantle. Although, eventually, no long-term mission was approved by IODP, the scientific objectives related to deep drilling in the ocean crust remain essential to our understanding of the Earth. These objectives are to:

- Determine the geological meaning of the Moho in different oceanic settings, determine the in situ composition, structure and physical properties of the uppermost mantle, and understand mantle melt migration,
- Determine the bulk composition of the oceanic crust to establish the chemical links between erupted lavas and primary mantle melts, understand the extent and intensity of seawater hydrothermal exchange with the lithosphere, and estimate the chemical fluxes returned to the mantle by subduction,
- Test competing hypotheses of the ocean crust accretion at fast spreading mid-ocean ridges, and quantify the linkages and feedbacks between magma intrusion, hydrothermal circulation and tectonic activity,
- Calibrate regional seismic measurements against recovered cores and borehole measurements, and understand the origin of marine magnetic anomalies,
- Establish the limits of life in the ocean lithosphere.

The "MoHole" was planned as the final stage of Mission Moho, which requires non-riser and riser drilling, geophysical site surveys and the development of new technology including the construction of a +4000 m riser. Initial expeditions would use existing drilling capabilities to sample shallow and deep targets in increasingly hostile conditions in ocean crust formed at both fast and slow spreading rates, allowing us to deliver major short-term science returns while we develop the equipment, technology and experience to tackle a full crustal penetration.

The first, short-term milestone is to return in IODP Hole 1256D, into intact crust formed during a period of superfast spreading (> 200 mm/yr) on the East Pacific rise 15 million years ago, and drill as deeply as possible with non-riser technology. The first gabbroic rocks below the sheeted dikes were encountered at the end of IODP expedition 312 at 1407 meters below seafloor. They mark the interface between the axial melt lens and the base of the hydrothermal system. Future deepening to a minimum of a few hundred meters should recover cumulate gabbros that will further constraint accretion mechanisms of the lower, igneous crust.

Relict oceanic textures and minerals in the Ultramafic Rocks of the Antrona Metaophiolite (Western-Central Alps, Italy

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The Antrona ophiolite (Western-Central Alps) represents a tectonic fragment of the Upper Jurassic-Lower Cretaceous Western Tethyan Ocean involved into subduction during the convergence between the European and African plates. The Antrona ophiolite occurs at the lower structural levels in the Alpine nappe stack, between the overlying Upper Penninic Monte Rosa nappe and the underlying Middle Penninic Camughera-Moncucco nappe. Despite the intense tectono-metamorphic reworking due to the Alpine history, the Antrona ophiolite shows all typical lithologies of the oceanic lithosphere. The ultramafic portion here described is composed of dominant massive serpentinite and minor mylonitic serpentinite including dunite layers, amphibole-rich boudins, and pyroxenite layers consisting of recrystallized clinopyroxene porphyroblasts, chlorite, and opaque minerals. The mafic portion is mostly represented by amphibolites which often retain relict magmatic texture (flaser gabbro), but show a pervasive foliation close to the tectonic contact with the Camughera tectonic unit. Microstructural and mineralogical analyses of selected ultramafic samples show that olivine, clinopyroxene, and spinel still preserve relict mantle textures. Olivine porphyroblasts exhibit evidence of intracrystalline deformation like “deformation lamellae”, which evolve on a unique slip plane system. Spinel occurs as “holly-leaf”-shaped grains mantled by a chlorite corona. Clinopyroxene porphyroclasts still retain relict exolution lamellae now filled with opaque minerals. These microtextures recall typical mantle structures which are recognizable either in well preserved ophiolitic complexes, such as the Semail ophiolite (Oman), or along the modern slow and ultraslow spreading ridges.

Microchemical analyses carried out on these phases highlight compositional pecularities. Olivine composition varies from Fo_{87} and $Fo_{87.9}$ which is not comparable with the composition of most mantle olivine from modern oceanic settings (Fo90-Fo91). This inconsistency might be explained either by recrystallization of olivine during the Alpine stage, or by the effect of metasomatic processes acting during oceanic serpentinization, such as “silica metasomatism” that caused a re-equilibration of major elements (Si-enrichment and Mg-loss) (Manning 1994, 1995, 2004; Bach et al., 2006; Alt et al., 2007). Spinel is a ferritchromite always rimmed by chromian-chlorites. This assemblage has been referred to a metasomatic process (Mellini et al., 2005) that occurs during prograde metamorphic conditions after serpentinization and involves original chromite and antigorite (Merlini et al., 2007). Clinopyroxene composition is close to diopside end member. XRD analyses confirm serpentine of the ultramafic rocks is mostly antigorite. These observations support the hypothesis that the Antrona ultramafic rocks represent a sub-oceanic mantle slice involved in the Alpine orogeny and now transposed with portions of the oceanic crust. Mantle textures are preserved in spite of the fact that the original chemical system has been changed by metasomatic processes. The orogenic Alpine history is marked, in some ultramafic rocks, by the occurrence of olivine and tremolite that are in textural equilibrium. In mafic rocks, amphibole shows compositional zonation with actinolitic cores and tschermakite-edenite rims; plagioclase is zoned with albitic cores and anorthitic rims. Such chemical evidences suggest a general temperature increase tracking the transition from greenschists to amphibolite facies metamorphism during the late Alpine evolution.

Hydrothermal Systems and Oceanic Detachment Faults: Controls on the Rheology and Structural Evolution of Slow-Spread Ocean Crust

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and the IODP Expedition 304/305 Scientific Party, JR63 Scientific Party.

It has recently become clear that detachment faulting leading to oceanic core complexes (OCCs) is an important process in the formation of oceanic lithosphere, with perhaps 30% of the Atlantic ocean floor being produced by processes including detachment faulting. Two end-member types of detachment fault have so far been characterised: "Cold" detachments are typified by talc-tremolite chlorite schists showing evidence for intense hydrothermal alteration, gabbroic intrusions into footwall serpentinites that lack significant high-temperature (>700 ºC) deformation fabrics, and by extensive evidence for syntectonic intrusion of basaltic dykes or sills within and immediately below the fault zone. The footwall gabbros appear to have cooled rapidly from magmatic temperatures but show extensive evidence for alteration under greenschist and low amphibolite conditions (300-650 ºC). Detachments of this type have been well studied at 30º N and 15º 45' N in the Atlantic. The main example of a "hot" detachment is the Atlantis Bank on the Southwest Indian Ridge, where ODP Hole 735b revealed a thick mylonite zone in gabbroic rocks with the dominant fabrics forming at >800 ºC, and evidence for only moderate hydrothermal alteration. The high temperature shear zone appears to have formed over a period of about 200 kyr.

Recent studies at the TAG hydrothermal field have revealed a steep, arcuate zone of microseismicity reaching 7 km below seafloor between the TAG mound and the neovolcanic zone (NVZ). This has been inferred to be part of an active detachment fault, linking with a shallow aseismic portion passing beneath the TAG field. A plausible model is that the TAG hydrothermal fluids are channelled up the detachment from depth, leaving it to break through the hangingwall basalts 4.5 km from the NVZ. The temperature of the hydrothermal fluids is comparable to the metamorphic temperatures inferred from the talc-tremolite-chlorite schists on exposed cold detachments.

We suggest that the thermal regime in cold OCCs is buffered by flow of hydrothermal fluid up the detachment, and that this controls the rheology of both the fault rocks and the footwall, cooling the ridge crest lithosphere to < 700 °C down to depths of 7 km below seafloor. Hot detachment faults form where there is no active hydrothermal system, with much slower cooling of footwall gabbros allowing the development of extensive mylonites.

A study of fluid inclusions from superfast spreading crust

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Fluid inclusions offer the only available samples of uncontaminated sub-seafloor fluids. To date, microthermometry of such fluid inclusions trapped in ocean crust rocks has revealed that fluids of a wide range of salinities exist in both modern and ancient hydrothermal systems. LAICPMS analyses of fluid inclusion chemistry are reported here. This method allows assessment of multiple populations of fluids within the same sample, giving information on the full range of fluids, rather than simply bulk compositional data.

Samples from different pseudo-stratigraphic levels in ODP/IODP Hole 1256D were studied. The site is host to two main fluid types, the first of which is a lower salinity fluid (Type I), exhibiting a greater range of salinities (0.5-22.4 $NaCl_{equiv}$ wt.%) than black smoker vent fluids (~1.5-7 $NaCl_{equiv}$ wt.%) and with trapping temperatures (up to ~497˚C) often greater than black smoker fluids (up to ~403˚C). This fluid Type is present at all levels studied. The second fluid is a hypersaline brine (Type II) which is restricted to the lower levels of the hydrothermal system. Both Type Ia (salinity less than seawater) and Type Ib (salinity greater than seawater) inclusions are found with the range of salinities encountered explained by phase separation and back-mixing with seawater. A mechanism for the generation of hypersaline brine phases is not as straight-forward, yielding an inconclusive verdict in considering magmatic brine exsolution and phase separation.

Laser ablation of the fluid inclusions has revealed evidence for efficient uptake of metals into the fluid (Na, Mg, K, Ca, Fe, Cu, Zn, Sr, Ba and Pb). Elemental concentrations are generally elevated with respect to vent fluids. However, simple mixing models do not explain these concentrations and therefore it is clear that these fluids must arise from a complex set of occurrences in addition to phase separation and back-mixing. Data suggest inclusion chemistry is affected by albitisation and transition metal leaching, demonstrating the influence of fluid-rock interaction on fluid chemistry and other processes of this type might also contribute. Magnesium loss from the fluid is apparently slow with it being present in all fluid populations studied.

Alteration sequence of gabbroic rocks from Atlantis Massif (IODP Hole U1309D) and its tectonic implications

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Relatively fresh rocks recovered from deep boreholes at the ocean floor are not affected by pervasive alteration, and therefore provide an opportunity for studying alteration sequence on the basis of textural relationships between alteration minerals that formed at different physico-chemical conditions. Alteration sequence is a record of cooling history of the oceanic lithosphere and hydrothermal activities, and is a key to understanding tectonic processes near slow-spreading axes, where alteration has an important role on tectonic development of the lithosphere. In this context, I put great emphasis on careful observations of rock textures and non-destructive analyses of minerals that show complex modes of occurrence. As an example, I present the results of studies on alteration of gabbroic rocks from deep parts of IODP Hole U1309D at Atlantis Massif, which is an oceanic core complex tectonically exhumed from a lower crustal depth.

The gabbroic rocks contain alteration minerals that formed under upper amphibolite- to subgreenschist-facies conditions. The alteration minerals are unevenly distributed and commonly occur in the proximity to hydrothermal veins or igneous contacts between different gabbroic lithologies. The major efforts of our studies were identification of low-temperature minerals, estimation of thermal and chemical conditions for alteration reactions, and determination of temporal sequence of the reactions. For the analyses of clay minerals, we combined non-destructive analytical procedures: petrographic microscope, electron microprobe, Raman spectrometer and transmission electron microscope, and found that saponite and vermiculite were formed by the infiltration of seawater-derived oxidizing fluids. For the analyses of vein-related alteration halos, we carried out detailed observations of texture under the microscope and using back-scattered electron images, and theoretical consideration on the effect of silica and water activities on the stability of mineral assemblages, and found that amphiboles, chlorite and talc were formed by protracted or sequential infiltration of hydrothermal fluids under amphibolite-facies conditions. Consequently, we argued that the high-temperature and low-temperature alteration was a cause and a result, respectively, of relatively rapid exhumation of the oceanic core complex from a lower crustal level to a shallow, off-axis region.

Core reorientation using Formation MicroScanner images: application to the palaeomagnetic study of Atlantis Massif

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The inherent lack of azimuthal control on core material associated with the Integrated Ocean Drilling Program (IODP) is an ongoing problem. The dip of brittle features, such as veins or open fractures, can be measured directly on the core, but the strike of these features with respect to geographic north is not known. However, wireline logging data can provide a near-continuous record of the physical properties of the borehole wall. The Formation MicroScanner (FMS) tool images resistivity contrasts, and distinct inclined planar features can be identified by their sinusoidal shape on unwrapped images. Importantly, these structural features can be accurately oriented in the geographic co-ordinate system due to the inclusion of a magnetometer on the FMS toolstring. Therefore, features seen on the core can be correlated with features seen on the borehole wall, enabling full re-orientation.

This core re-orientation technique is applied to data from IODP Expedition 304/305, which sampled exhumed lower oceanic crust at Atlantis Massif, an oceanic core complex located on the western flank of the Mid Atlantic Ridge at 30°N. Hole U1309D reached a total depth of 1415 metres below sea floor (mbsf), had a high average core recovery of 74% and good quality FMS images. By re-orienting structural features seen on core pieces that have also been sampled for palaeomagnetic analyses, the resulting magnetic remanence directions are re-oriented into geographic co-ordinates. Consequently, we can perform a robust, fully quantitative analysis of the amount and axis of tectonic rotation during the development of the oceanic core complex. Results demonstrate a 46°± 6° counterclockwise rotation of the Atlantis Massif footwall around a Mid-Atlantic ridge-parallel horizontal axis trending 011°± 6°, consistent with rolling-hinge models for the development of oceanic core complexes.

Realistic Mohole using D/V Chikyu

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We propose realistic Mohole using D/V Chikyu. The basic policy is the same as the 21st Century Mohole; that is to drill a deep, full ocean crustal penetration hole through the Moho, and into the uppermost mantle at a single site to achieve a quantum increase in our understanding of Earth evolution. This drilling hole will be a deep reference hole of the ocean crust, because it is the first trial that the human performs. Therefore, the drilling site is required to show normal intact ocean crust with the typical Moho discontinuity formed at a fast spreading rate ridge system; crust formed at a slow spreading rate ridge system should be avoided for the drilling site because of their variety of crustal structure.

We emphasize to fully use an ability of riser drilling vessel Chikyu in order to make the Mohole an operationally realistic. The concrete plan of the realistic Mohole consists of following three phases.

Phase 1: Drilling with sampling drilling cuttings and with wall geophysical measurements using a Logging-While-Drilling (LWD) tool. This way allows us to save drilling time, which results in achieving the Moho penetration more realistically. Further, both of cuttings samples and geophysical measurement data from the entire ocean crust and the upper part of mantle are obtained continuously. It is the important point of this way to utilize these samples and data effectively.

Phase 2: Acquiring drilling core samples using branch moat and/or assistance aperture moat drillings at the most important sections.

Phase 3: Reserving the hole in order to further drilling and/or to acquire drilling core samples using the branch moat and/or assistance aperture moat drillings at some sections where their importance is newly found from the results of Phases 1 and 2.

Phase 1 and 2 will be performed by the Mohole project, and Phase 3 would start corresponding to a new proposal after achievement of the Mohole. In other words, this hole is placed with a window for the whole crust and the uppermost mantle, and drillings of branch moats and/or assistance aperture moats will be performed by adopting a proposal for drillings at certain depths in the same way as the proposal for drillings at certain places in ocean basins.

Scientific goals and objectives for the 21st Century Mohole are well documented in Mission Moho workshop report (2006). We suggest one additional aspect, which is based on recent high quality seismic surveys in the western Pacific using air-gun, multi-channel streamers, and ocean-bottom seismometers. The results of the seismic surveys indicate that Moho discontinuity is not ubiquitously present and the amplitudes of discontinuous reflectors vary in space. Furthermore, velocity structure of ocean crust and of uppermost mantle is not uniform, but it has variety even if it was formed at a fast spreading rate ridge system. A combination of high quality seismic surveys and Mohole drilling is an essential approach, because the Mohole drilling provides a reference for the structure, which makes extreme difference to interpret the velocity structure obtained from the high quality seismic surveys. On the other hand, the seismic surveys provide us with the spatiality of a similar velocity structure and the variation of velocity structure in space (or in different crustal age). Further combinations with land studies of ophiolites, laboratory measurements of rocks, and technically and scientifically improvements to use cuttings samples and geophysical measurement data, are required. As the results, these combinations would provide us with critical information to understand the nature of the crust, the Moho discontinuity, and the upper most mantle, and also dynamic processes forming the oceanic crust.

Composition and structure of Oceanic Core Complexes

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Oceanic Core Complexes are increasingly recognised as important components of slow-spreading Mid-Ocean Ridges. They reflect a mode of lithospheric accretion that is very different from classical magmatic sea-floor spreading, and offer important tectonic windows into deep crust and uppermost mantle. OCCs appear to form in response to lowered melt flux to the surface; they involve direct exhumation of lower crust and upper mantle and long-lived slip on detachment faults that root deep beneath the spreading axis. These faults provide important pathways for ingress of seawater and circulation of hydrothermal fluids. Recent work including our own has greatly improved the geophysical and geological characterisation of a number of core complexes, and will be summarised in the poster. Further work is planned. Even now there are sites with considerably better characterisation than was the case for the IODP drilling of the core complex at Atlantis Bank (North Atlantic), and the situation is likely to improve further over the next few years. We can now propose testable models of OCC structure, including likely positions of moho outcrop. The time is thus ripe to consider further drilling, including carefully sited arrays of shallow holes and one or more deep ones, to test these structures and investigate the composition, structure and alteration of deep crust and uppermost mantle.

Reconstructing Mid-Ocean Ridges to understand the Mid-Cretaceous Seafloor Spreading Pulse

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Two main hypotheses compete to explain the Mid-Cretaceous global sea-level high-stand: a massive pulse of oceanic crustal production that occurred during the Cretaceous Normal Superchron (CNS) and the "supercontinent break-up effect", which resulted in the creation of the mid-Atlantic and Indian Ocean ridges at the expense of subducting old ocean floor in the Tethys and the Pacific. We have used global oceanic palaeo-age grids and a reconstruction of the global mid-ocean ridge system, to test these hypotheses. Our models show that a high average seafloor spreading rate of 92 mm/yr in the Early Cretaceous that decreased to 55 mm/yr during the Tertiary with peaks of 86 mm/yr and 70 mm/yr at 105 Ma and 75 Ma, respectively, correspond to the two observed sea-level high-stands in the Cretaceous. We find that the average age of the ocean basins through time is only weakly dependent on the choice of timescale although the GTS2004 timescale does diminish the seafloor spreading high in the Cretaceous. The expansive Mid and Late Cretaceous epicontinental seas, coupled with warm climates and oxygen-poor water masses, were ultimately driven by the younger average age of the Cretaceous seafloor and faster seafloor spreading rather than a vast increase in mid-ocean ridge length due to the break-up of Pangaea or solely on higher seafloor spreading rates, as suggested previously. Our results also provide estimates of the global mid-oceanic ridge system and global crustal production throughout the Cretaceous and Cenozoic which can be used to calculate parameters such as global heatflow, hydrothermal fluid flux, oceanic porosity and CO_2 content important for studies of ocean chemistry.

Constraints on the Fluid Evolution during Mid-Ocean Ridge Hydrothermal Circulation from Anhydrite sampled by ODP Hole 1256D.

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Understanding the evolution of the seawater-derived fluids in active mid-ocean ridge hydrothermal systems (which act as the major heat and chemical transport device) is critical to gaining insights into many aspects of hydrothermal systems in the ocean crust. These include the geometry of recharge and discharge pathways, the relative importance of ridge axis and ridge flank circulation, and the nature of chemical and thermal fluxes. Anhydrite ($CaSO_4$) is a potentially useful mineral for recording the evolution of seawater-derived fluids during mid-ocean ridge hydrothermal circulation because it exhibits retrograde solubility and precipitates from seawater at temperatures greater than $>120^{o}C$ Anhydrite can precipitate due to the simple heating of seawater, and reaction with basalt, or through mixing of seawater-derived recharge fluids with upwelling, hot black smoker fluids.

New insights into the chemical and thermal evolution of seawater during hydrothermal circulation through analyses of anhydrite recovered from ODP Hole 1256D are based on measurements of $^{87}Sr/^{86}Sr$, major element ratios, REE and $\delta^{18}O$. These data suggest that the vast majority of sulfate is returned to the oceans as warm (as yet undetected) diffuse fluids near the axis. The presence of two chemically and petrographically distinct anhydrite groups, and anhydrite forming at temperatures in excess of $400^{o}C$ suggest rapid mixing of low Sr, SO_4-bearing, seawater with high Sr, no SO_4, hydrothermal fluid.

Influence of serpentinization on the light element budget of the oceanic plate

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During residence in the ocean, fluid-rock interactions alter the oceanic plate and new hydrous-minerals form (e.g. clay, calcite or serpentine). During subduction these minerals liberate fluids, leading to partial melting in the mantle wedge and the erupting melts form the arc volcanoes. It is therefore important to understand alteration processes to understand the element cycle through the subduction zone. As light elements are highly fluid mobile, they can be used to study such processes.

Serpentine is known to be a major carrier of H_2O to depth (15 wt%; Ulmer and Trommsdorff, 1995) and fluid-mobile elements might be liberated at that depth. Our study on ODP Leg 209 serpentinites from the mid-Atlantic ridge showed that during alteration boron is highly enriched in the ultramafic rocks, while Li is mostly leached (Vils et al., 2008). Based on our results and on literature data, we calculate the inventory of B and Li contained in the oceanic lithosphere, and their partitioning between crust and mantle as a function of plate characteristics. If the plate is young or old, from a fast- or a slow-spreading ridge, the boron budget of the oceanic plate is dominated by serpentinites. The lithium budget, in contrary, is mostly dominated by the sedimentary or mafic part of the oceanic plate. As up-to-date depth of serpentinization is poorly constraint (e.g. Minshull et al., 1998; Ranero et al., 2003) this seams for light element cycling an important parameter to solve. Additionally, for modeling of subduction zones in general this helps constraining the amount of fluid available at the different depth.

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Fluid mixing and thermal regimes beneath the PACMANUS hydrothermal field, Papua New Guinea: Helium and Oxygen isotopes

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PACMANUS sits atop Pual Ridge in the East Manus Volcanic Zone, Papua New Guinea, and displays varying venting styles from low temperature (~6ºC) 'shimmering water' venting at Snowcap to high temperature (~360ºC) black smoker venting seen at Roman Ruins and Satanic Mills. Drilling during ODP leg 193 explored these sites in the third dimension, allowing a picture of the subsurface at PACMANUS to be built. The site is of interest economically – both as an analogue for ancient felsic-hosted systems and as a possible economically viable deposit; sulphide chimneys have been shown to contain on average 7 wt% Cu, 24 wt% Zn, 16 ppm Au and 230 ppm Ag (Binns et al. 2004).

Fluid mixing processes and thermal regimes beneath PACMANUS were investigated using $^{3}He/^{4}He$ ratios from fluid inclusions within pyrite and anhydrite precipitates and the $\delta^{18}O$ signature of anhydrite. Depressed $^{3}He/^{4}He$ ratios of 0.2 – 6.91R_A show a radiogenic component to the helium, likely to be in-stu radiogenic production of ^{4}He. $^{40}Ar/^{36}Ar$ ratios are slightly elevated above seawater (295-302), indicating the majority of Argon is seawater derived, with a minor percentage leeched from the source rock or directly degassed. $\delta^{18}O$ anhydrite precipitation ratios are 6.5 to 11 for Snowcap and 6.4 to 11.9 for Roman Ruins. In comparison with anhydrite trapping temperatures (Vanko et al. 2004), the anhydrite-water system is likely to have not reached equilibrium and so does not allow for the application of a geothermometer.

Drawing on these results and others, a simple mixing model has been constructed whereby the differing venting styles observed at Snowcap and Roman Ruins are explained by a lower supply of hydrothermal end-member at Snowcap. This allows greater proportions of seawater in mixing events, cooler temperatures, less vigorous venting and a detectable magmatic sulfur component. In contrast, Roman Ruins receives a greater volume of hydrothermal end member which is able to reach the surface with little fluid mixing and in greater volumes, allowing more vigorous venting and hotter venting temperatures. This reduces the venting style conundrum to a simple idea: less energy into the system at Snowcap than at Roman Ruins. It requires a plumbing system at depth which favours the supply of hydrothermal end-member to the high temperature sites.

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