Thematic Review

Report Series No. 2

Oceanic Crustal Structure and Formation

IODP and ODP Achievements November 2002 – December 2005

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Front cover: top left – new and used coring bits, damaged bit was used during coring extremely hard recrystallized dikes during IODP Expedition 312; top right – D/V *JOIDES Resolution* (photo by D. Anderson, NOAA/National Geophysical Data Center); bottom – mantle/crust transition zone ("Paleo-Moho discontinuity") in the Oman ophiolite, top of the hill is made of layered gabbros, the fore-ground is exposure of mantle derived harzburgites and the yellowish-brown horizon in between the gabbros and the harzburgites is the dunitic transition zone (photo by Georges Ceuleneer).

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Executive Summary

Background

The formation and alteration of the oceanic lithosphere are important components of the Solid Earth Cycles and Geodynamics theme of the IODP Initial Science Plan (ISP). This report reviews findings within these areas by IODP and two of the final legs of ODP. Results from ocean drilling and other studies at the time the ISP was written suggested that there are two fundamental end-member classes of oceanic crust: (1) Fast-spread crust in which the ambient melt supply is able to keep up with the extension of the lithosphere and to generate a regular, layered, fully igneous crust ('Penrose' ophiolite model, 1972); and (2) slow-spread crust in which the melt supply is insufficient to keep up with extension, and is supplemented by tectonic extension. In the latter case the tectonic extension in places exposes, at the seafloor, deep crustal to upper mantle sections. That mantle rocks exposed on the seafloor are serpentinized suggests that the seismic boundary of the Mohorovičić seismic discontinuity (Moho) might be an alteration front between unaltered peridotite and overlying serpentinite, as originally proposed by Harry Hess in 1962. Such a view is in stark contrast to the ophiolite model, which views the Moho as the transition from lower crustal gabbro to mantle peridotite, and the seismic layer 2/3 boundary in oceanic crust as the transition from upper crustal and sheeted feeder dike complex to lower crustal gabbro formed in the axial magma chamber. In general, slow-spread crust is assumed to be tectonically dismembered ophiolitic crust lacking, pending degree of tectonic extension, one or more components of ophiolitic crust. The ISP therefore made it a high priority to recover, as a reference, intact and tectonically undisrupted deep sections of oceanic crust within fast-spread crust. The ultimate goal has long been, and remains, to recover a complete crustal section including the Moho and uppermost mantle ("21st Century Mohole' Initiative" of the ISP). Another important ISP goal was to constrain the variability of slow-spread crust. Partly based on successful ODP drilling at rifted margins (e.g., Legs 210, 173 and 149), testing weather, in severely magma starved settings, the Moho represents an alteration front within a mantle protolith (i.e., Hess-type Moho) became an objective. Drilling experiments targeting fast- and slow-spread crusts were initiated by ODP through two different expeditions (Legs 206 and 209). IODP successfully continued these efforts, addressing fast-spread crust during Expeditions 309 and 312 (deepening Hole 1256D, initiated by ODP Leg 206). IODP Expeditions 304 and 305 targeted slow-spread, and presumably magma-starved crust, along the Mid-Atlantic Ridge along which ODP Leg 209 drilled a transect parallel to the ridge.

Fast-spread crust

ODP Leg 206 and IODP Expeditions 309 and 312 were based on a proposal to drill approximately 1.5 km into the 15-Myr-old oceanic crust at Site 1256 within the Guatemala Basin. This crust originally formed at superfast rates (200-220 mm yr-1) along the East Pacific Rise. Before drilling, it was hypothesized that this crust (1) in general would have a regular Penrose type layered magmatic internal structure; and (2) the upper oceanic crust (extrusives and sheeted dike complex) would be anomalously thin and thus provide an opportunity to reach the sheeted dike to lower crust (gabbro) transition at an unprecedented shallow depth (seismic layer 2/3 transition at 1275–1550 mbsf). ODP spent eight expeditions at Site 504 (intermediate spreading rate) to drill 2111 mbsf without ever achieving full penetration of the minimum 1050-m-thick dike complex, which was found to host the transition from seismic layer 2 to layer 3. Expedition 312 successfully deepened Hole 1256 (initiated by Leg 206 and Expedition 309) to 1507 mbsf and recovered gabbroic material within its lowermost part. The current base of the hole, however, is in diabase. It is therefore most likely that Hole 1256D has penetrated deeply into the dike-gabbro transition, however, without recovering material from main plutonic section of the lower crust. Notably, Site 1256 – unlike Hole 504B – has not reached the transition into seismic layer 3.

This historical achievement of full penetration of the upper oceanic crust into the transition to lower crust was facilitated by both excellent drilling supervision, as well as the presence of an unexpected thin layer of sheeted dikes, only about 350 meters thick, and therefore presenting less challenging drilling conditions compared to Hole 504B. The relatively thick extrusive carapace (800 m) comprised many thick and quite massive lava flows. High temperature alteration of the lowermost dikes (granulite facies contact metamorphism) suggests that a convecting magma chamber was once present immediately below them, and hence, that a full penetration of the transition zone into melt lens rocks and then truly lower crustal, cumulus gabbros is imminent. Given the uncertainties in depth to the seismic layer 2/3 transition, it is therefore still possible that this acoustic boundary and the full and final transition to a lower gabbroic crust coincide at Site 1256. However, paired with observations from Hole 504B and from studies on slow-spread crust, it seems evident that seismic velocities, although related to different primary lithologies, are significantly affected by alteration and metamorphism.

Hole 1256D gabbros are of basaltic bulk composition overall, and therefore cannot be the complementary cumulate residues from an axial magma chamber. Instead, by analogy to the Oman ophiolite, more primitive cumulate gabbros representing truly lower oceanic crust are expected at depth. The operational options for further deepening of Hole 1256D are fair to good. The predominant lithology below the bottom of the hole is expected to be gabbro for which good hole stability and relatively easy drilling can be expected. The success of ODP Leg 206, and IODP Expeditions 309 and 312, have therefore positioned IODP to achieve a potentially major milestone towards the “21st Century Project Mohole” before the end of the current phase of IODP. Recovery of a few hundred meters of a lower crustal gabbro sequence would enable much improved benchmarking of the ophiolite model, and potentially provides constraints on much discussed models for lower crustal accretion.

Additional and very noteworthy accomplishments include the confirmation by Expedition 312 of the suggested inverse relationship between thickness of upper ocean crust and spreading rate, the unexpected partitioning of the upper crust into a relatively thick extrusive carapace of unusually thick and massive lavas, and the presence of a relatively thin dike complex. Evidence for a high paleo-geothermal gradient is demonstrated, suggesting that a strong thermal boundary layer was established between an upper convective hydrothermal cooling system and a lower convective magmatic heating system. A diverse and in part high impact record of publications has resulted from the successful drilling endeavor represented by ODP Leg 206 and IODP Expeditions 309 and 312.

Slow-spread crust

Two drilling campaigns have addressed slow-spread crust formed along the Mid-Atlantic Ridge. ODP Leg 209 drilled a ridge-parallel transect of relatively shallow holes within a supposedly magma starved ridge segment bounded by transform faults approximately around the 15°-20° N Fracture Zone. IODP Expeditions 304 and 305 attempted to drill a transect across a ridge flank around 30° N.

The primary aim of Leg 209 was to test the hypothesis that mantle flow and melt extraction along slow-spread ridges might be focused at the centers of ridge segments. However, two key observations were made: (1) mantle deformation fabrics are ubiquitously weak except where localized along high temperature shear zones; (2) significant proportions of gabbroic rocks intruded the mantle peridotite at locations both near and far from the fracture zone. The hypothesis of melt focusing toward the centers of ridge segments is therefore not supported by the observations from Leg 209. Likewise, drilling results suggest that the mantle peridotites exposed on the seafloor or at the shallow depths reached by drilling did not undergo intense penetrative deformation. One explanation of this unexpected observation is that these peridotites were never processed in a mantle upwelling region, in which relatively high shear strains are expected. A likely explanation is that they instead reached shallow depths in response to deformation localized on major lithospheric shear zones. An observed prevalence of distributed melt impregnation over melt focused into channels contrasts with observations made in ophiolites. Combined with the unexpected frequency of gabbroic bodies hosted by the mantle peridotite, this suggests that significant quantities of melt may therefore be generated beneath this supposedly 'magma-starved' ridge, but that much of it may be trapped and solidified in the mantle as it is transformed into lithosphere beneath the ridge axis.

Expeditions 304 and 305 were based on a single proposal to drill a transect across a ridge flank north of a ridge-transform inner corner. Atlantis Massif is a major oceanic core complex, with spreading parallel corrugations, that rises to shallow depth north of the northern inside corner of the Atlantis transform fault. Observations made prior to drilling, led to the interpretation that this represented an unique area in which serpentinized mantle possibly translated at around 800 m depth into more pristine mantle peridotite. Towards the ridge axis the massif is overlain what is interpreted as an overriding hanging wall of volcanics separated from the footwall massif by a major detachment fault. One of the original objectives had been to drill through these extrusives in order to penetrate the hanging wall and thereby sample the entire detachment fault zone sub-surface. Drilling difficulties related to bare rock drilling of the young extrusives ultimately prevented this from being achieved; however, the volcanic nature of the hanging wall was confirmed. The planned deep drilling into the footwall was exceptionally successful at Site U1309 (1656 m water depth) resulting in a 1415.5-m-deep hole of excellent stability and with a very high average recovery (75 %). However, the recovered lithology was a surprise – extremely limited proportions (<0.3 %) of mantle peridotite material, but a predominance of gabbro (91.3 %, mostly very primitive), ultramafics (including troctolites; 5.7 %), and diabase (3 %). Site characterization by submersible shows that along its southern transform boundary the Atlantis Massif comprises major outcrops of serpentinite and talc schists hosting the famous 'Lost City' hydrothermal field. Consistent with the observations from Leg 209, this finding suggests, that the minimum 1.4-km-thick gabbro body sampled by Site U1309 is a discrete body hosted within a mantle protolith.

The very high recovery and relatively low degree of deformation and alteration have allowed very detailed studies of the gabbro body. In no place does it show the cyclically layered nature typical of gabbro in ophiolites; instead, high-resolution zircon dating of distinct magmatic units shows an extended history of multiple magma pulses feeding into the gabbro body. The excellent recovery has allowed core to be reoriented relative to logging images of the drill hole. Detailed paleomagnetic work on cores with a known azimuthal orientation shows a bulk rotation consistent with a 'rolling hinge' flexural unloading model for the detachment fault footwall. Expeditions 304 and 305 therefore provided a milestone in terms of understanding tectonic extension at mid-ocean ridges, and completely disproved the original hypothesis for the nature of this core complex.

In conjunction with the Leg 209 observations, a new model for the structure and working of slow-spread ridges emerges. They are probably less magma starved than hypothesized, but melt is retained in the upwelling mantle as it ascends, and becomes incorporated into a relative thick lithosphere. The latter deforms and extends along localized zones of deformation, some of which become major detachment faults operating via the rolling hinge model. Such detachment faults may therefore at least locally constitute the de facto plate boundary. Also, and equally important, is that the notion that slow-spread crust is may be broadly comparable to dismembered ophiolitic crust is likely to be quite wrong. The panel is impressed by the broadness of scientific investigations made and published on slow-spread crust studies.

Concluding comments

Overall, the final activities of ODP and initial IODP activities in the study of oceanic crustal formation and structure have been very successful. Moreover, such work proves that it is a field where new and surprising scientific results of first-order significance still can be made, and that it involves a vibrant scientific community. Results achieved no doubt need be included in textbooks. In the case of slow-spread crust in particular, results mandate re-education of the geosciences community as to the spectrum of fundamental processes operating at this type of plate boundary.

Future research at slow-spread ridges should have very high scientific potential, but the complexity of the problems now posed by the recent results will necessitate a very well-planned and integrated approach, with geological and geophysical mapping working in concert with both shallow and deep drilling. The panel sees the reoccupation of the milestone Hole 1256D, within fast-spread crust, as a low-hanging and achievable fruit within the current phase of IODP, but it also recommends that a scientifically and technologically long-term momentum towards a mission Moho be maintained. For this the development of a truly deep water (4 km+) riser drilling capability is a pre-requisite.

The review also noted areas where improvements can be made in the future: microbiology and material fluxes research can be strengthened; better integrated geophysical, shallow coring and deep drilling experiments can be designed; new geophysical observations in fast-spread crust can define new research foci and drilling strategies; and new, improved coring technology can be developed and tested (e.g., in young volcanics, reducing magnetic overprint, orientation of cores). Significant potential exists for enhanced cross fertilization between ocean drilling studies of ocean crust and studies of ophiolites. Finally, the panel concludes that the significant achievements in understanding the ocean crust by late ODP and early IODP efforts were achieved only because ambitious, multi-expedition experiments were planned and scheduled. Future success in drilling will depend on the ability to maintain focus and goals over a long period of time and to integrate with other disciplines.

1. Introduction

Scientific ocean drilling is rooted in the quest to study the ocean crust and its interface with the underlying mantle – the Mohorovičić discontinuity (Moho). Since the initial efforts 50 years ago (Project MOHOLE, 1958), Deep Sea Drilling Project (DSDP) starting in 1968, and later Ocean Drilling Program (ODP) devoted significant efforts to understand the formation of oceanic crust by sea-floor spreading, a fundamental element in plate tectonics. The formation and alteration of the oceanic lithosphere remained a scientific focus in the Solid Earth Cycles and Geodynamics section of the IODP Initial Science Plan (ISP) published in 2001 shortly before the termination of ODP in 2003.

In the 40-year history of scientific ocean drilling programs, a limited number of sites have been drilled deeply into truly oceanic basement (Fig. 1.1). Building on the discoveries made by DSDP and ODP, the ISP concluded that while the simple, layer-cake 'Penrose' ophiolite model (1972) of oceanic crustal structure was broadly supported from the study of obducted oceanic lithosphere, structural differences between fast- and slow-spread crust observed by ocean drilling suggests that there are (at least) two end-member classes of ocean crust: (1) Fast-spread crust in which the ambient melt supply is able to keep up with the extension of the lithosphere taking place at the divergent plate boundary (ophiolitic crust); and (2) slow-spread crust in which the melt supply does not keep up with extension, thereby requiring significant tectonic extension to accommodate the remaining component of plate separation. Such fault-assisted spreading seems at least locally to be associated with sea-floor exposure of serpentinized mantle peridotite. The latter observation has revived the pre-ophiolite

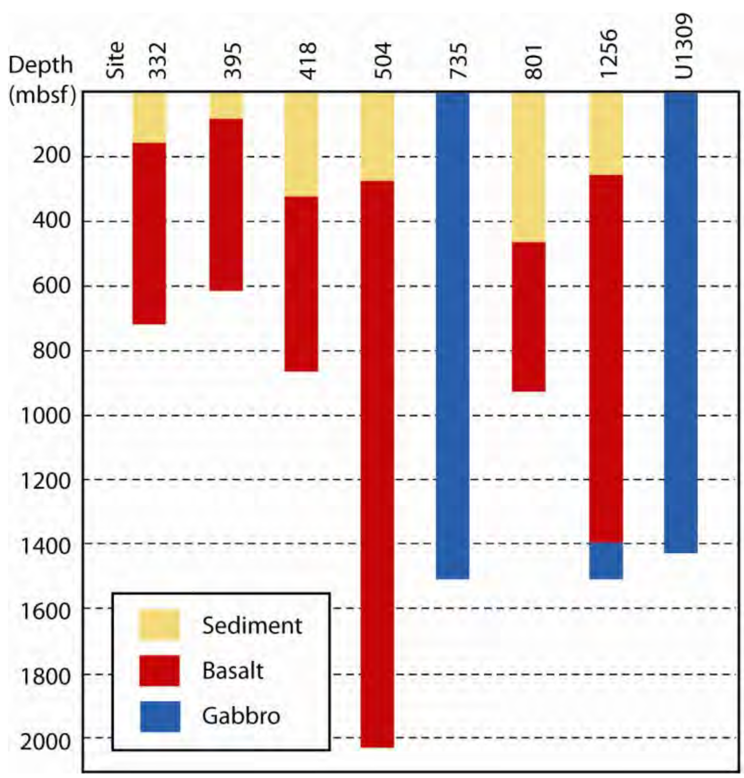


Figure 1.1 DSDP, ODP and IODP sites where significant (> 500 m) basement penetration was achieved. Excluded are deep basement sites 642 and 917 that were drilled in transitional crust along rifted margins and most likely floored by continental crust. Two (1256 and U1309) of the four deepest basement holes have been drilled by IODP. Sites with sediment and basalt on top represent efforts within intact oceanic crust. Sites with gabbro represent tectonic windows of opportunity to sample lower units of dismembered ocean crust (compiled by Jay Miller).

notion that the Moho is an alteration front between fresh peridotite and serpentinized peridotite, proposed by Harry Hess in 1962. This view also gained support from observations made at the apparently magma-starved Iberia and Newfoundland rifted margins (ODP Legs 149, 173, 210) at which serpentinite has been recovered in several locations from what was interpreted prior to drilling as igneous basement related to continental breakup.

By the time of the start of IODP in 2003 the general notion therefore was that the Penrose ophiolite model most likely applies only to fast-spread type crust. A major consequent implication of this notion is that we will probably not be able to address the processes of accretion of fast-spread lower crust by studying the (accessible) sections of lower crust exposed at slow-spreading ridges. The ISP therefore made it a high priority to recover intact and tectonically undisrupted deep sections of oceanic crust formed at fast spreading ridges. The ultimate goal was (and remains) to recover a complete crustal section including the Moho and uppermost mantle ('21st Century Mohole' Initiative of the ISP) in crust generated at a fast spreading rate in order to benchmark the ophiolite model, and constrain mechanisms of lower crust formation (e.g. the 'gabbro-glacier' versus 'sheeted sill' models of lower crustal accretion that are currently in vogue). Investigating the role and mechanisms of tectonic extension, magma generation and transportation within slow-spread crust were also high priorities of the ISP. Other objectives and goals include the understanding of alteration and serpentinization processes, magnetization of the crust, and in situ down-hole logging and sampling of seismic layering (such as the layer 2/3 boundary) to test the long-held assumption that they represent lithological transitions in a layer-cake ocean crust. Collaborative efforts with the InterRidge program in the study of ocean crust was also envisaged by the ISP, as well as comparative studies between obducted ophiolites and the deeper parts of in situ ocean crust.

Whilst it is clearly overly simplistic just to refer to two categories of 'fast' versus 'slow'-spread crust – magma supply plays a fundamental role in determining crustal architecture – we follow this terminology here because of its usage in the ISP. The drilling activities reported here targeted both fully intact crust from a fast spreading ridge and deeper levels of the lithosphere from a slow spreading ridge.

We emphasize that there is considerable variation in the internal structure of ophiolites, with many features either not well understood, or potentially specific only to ophiolites. Most ophiolites are believed to have formed above subduction zones, and subsequently deformed during obduction onto continental crust. It is therefore a gross oversimplification to regard ocean crustal drilling as simply ground truthing or benchmarking the ophiolite model, but nevertheless it is important to emphasize the continuing two-way nature of the exchange of ideas between ophiolite and ocean crustal studies.

In this thematic review of IODP achievements addressing 'Oceanic Crustal Structure and Formation' we first summarize in chapters 2 and 3 the general results from respectively fast-spread and slow-spread crust gained by IODP and the two related ODP expeditions Leg 206 (fast-spread) and Leg 209 (slow-spread). In subsequent chapters 4, 5 and 6 we present specific findings on the magnetization of the crust, alteration and microbiological processes, and comparison with ophiolite studies, respectively. In chapter 7 we address technological issues. Chapter 8 summarizes the main findings and presents recommendations for future work by IODP and related programs.

2. Studies of Fast-Spread Crust – Recovery of Intact Deep Crustal Sections

2.1 Introduction

IODP operations in fast-spreading ridge crust have been focused exclusively on Site 1256 in the Guatemala Basin (Fig. 2.1). This region is floored by oceanic crust that formed at spreading rates of 200–220 mm yr^{-1} (full rate), faster than any currently active spreading ridge. Over the course of three expeditions (ODP Leg 206; IODP Expeditions 309 and 312) Hole 1256D was drilled to a depth of 1507 mbsf, 1257 m into igneous basement (Fig. 2.2), penetrating the first ever complete sequence of volcanic extrusives and a sheeted dike complex, eventually to recover at 1407 mbsf, also for the first time, gabbro from in situ ocean crust (Teagle *et al.*, 2006; Wilson *et al.*, 2006).

Previous efforts to drill to gabbro through an intact section of upper crust had been concentrated on ODP Hole 504B, in 6.6 Myr old crust formed at the intermediate spreading rate Cocos-Nazca Ridge (98 mm/yr full rate). However, after eight DSDP and ODP legs and at 2111 mbsf (1836 m sub-basement), the attempt was thwarted whilst still in sheeted dikes by hostile drilling conditions and high temperatures. Learning the lessons of Hole 504B, the goal of operations at Site 1256 was to drill an optimally sited and engineered hole that could be re-entered over the course of a number of expeditions and eventually deepened such that in situ lower oceanic crust might be accessed for the first time. Complete crustal penetration into the upper mantle was never anticipated for this site.

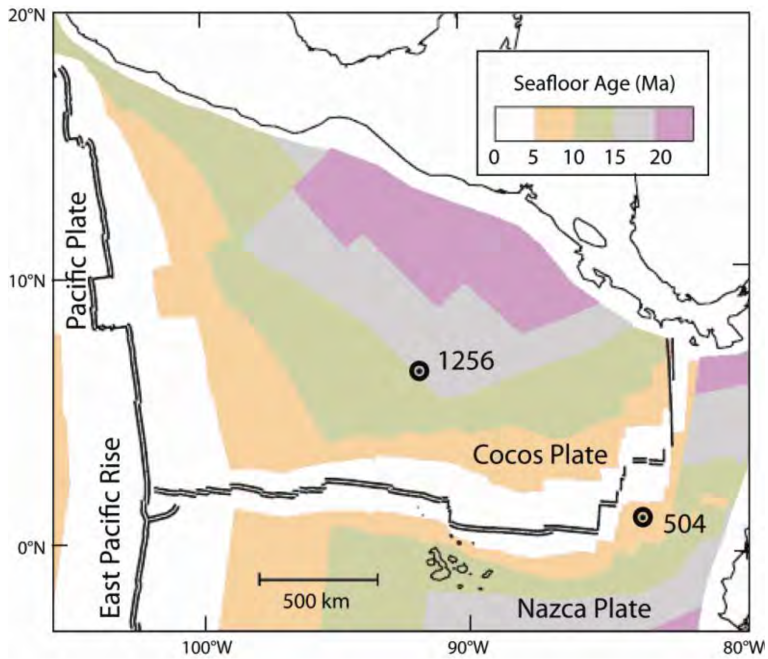


Figure 2.1 Age map of the Cocos Plate and East Pacific Rise, showing location of ODP Sites 1256 and 504 (from Wilson et al., 2006).

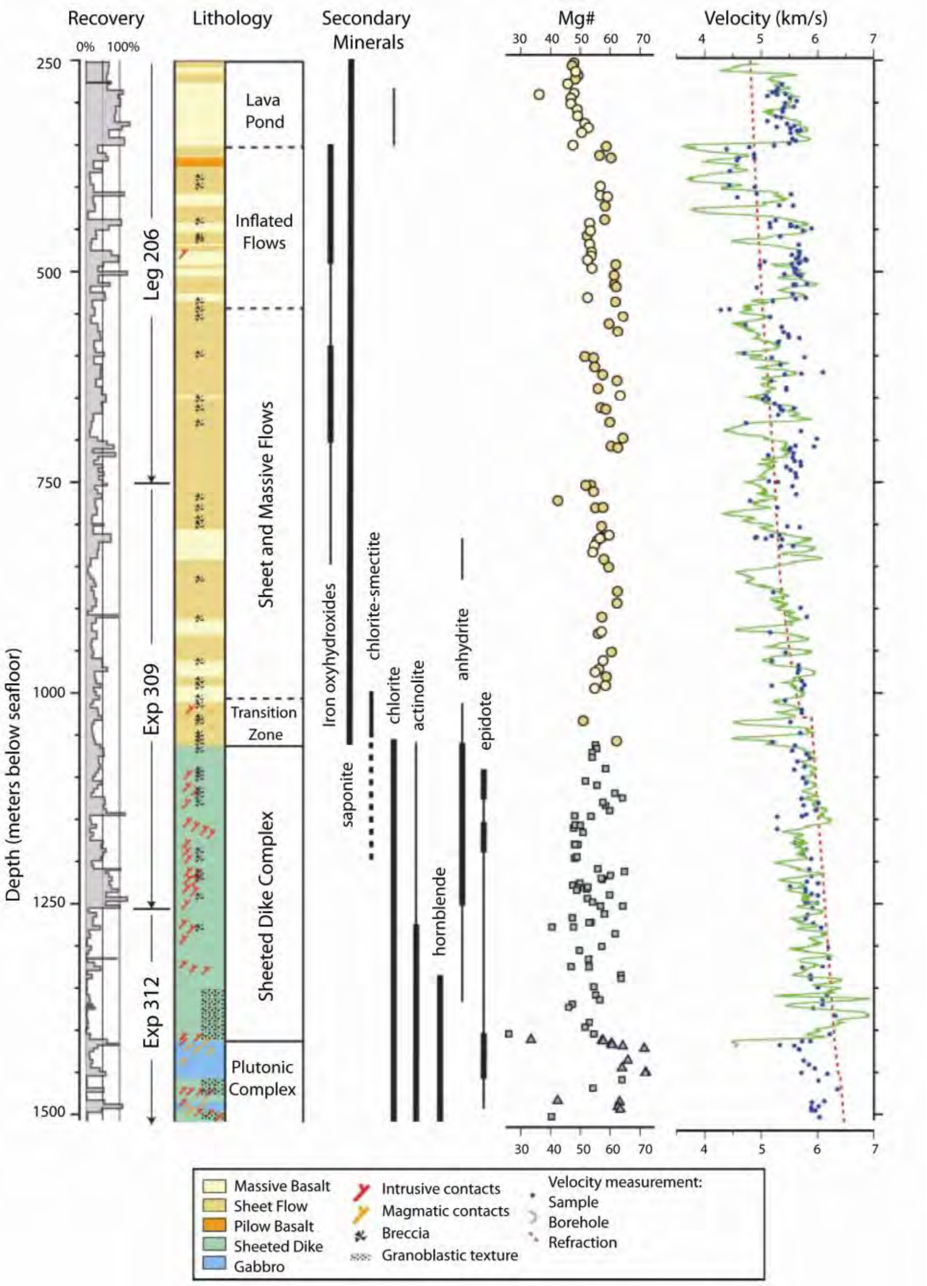


Figure 2.2 Summary lithostratigraphic column of the basement drilled to date at Site 1256 showing recovery, major lithologies, downcore index alteration, mineral distribution (thick lines – abundant; thin lines – rare), downcore distribution of Mg-number (where Mg# – 100 x Mg/(Mg + (0.9 x Fe)) atomic ratio), and seismic velocity measured on discrete samples, wireline tools, and seismic refraction (from Wilson et al., 2006).

Site 1256 is located at 6°44.2' N, 91°56.1' W in 3645 m water depth. It is situated ~1200 km northwest of Hole 504B, in 15 Myr old oceanic crust formed at the East Pacific Rise (Fig. 2.3). At that time this portion of the EPR was generating ocean lithosphere at the superfast rate of 200–220 mm yr^{-1} (full rate). The rationale for establishing a deep drill site at this particular location came from the apparent inverse relationship, found by seismic investigation of modern mid-ocean ridges, between depth to the top of the sub-axial melt body and seafloor spreading rate (Fig. 2.3; Wilson *et al.*, 2006). By extrapolating this relationship to the extreme spreading rates found in the Guatemala Basin, and accounting for off-axis lava flows and sedimentary overburden, it was predicted that gabbroic rocks could be encountered from as little as 1275–1550 mbsf, and therefore potentially be reached in only two expeditions.

The site was first occupied during Leg 206 in November 2002. After drilling three pilot holes to characterize the nature of the sedimentary overburden and uppermost basaltic basement, deep drilling commenced at Hole 1256D. Casing was set through the 250 m sediment interval and a further 20 m into basement. By the end of Leg 206 drilling had penetrated 502 m into basaltic lavas (752 mbsf), with 48% core recovery. The uppermost 284 m of this section were interpreted to be slightly later, off-axis lava flows. Hole 1256D was reoccupied twice in the first phase of IODP. In July – August 2005 Expedition 309 deepened the hole by 503 m, to 1255 mbsf, passing through the transition from lavas into sheeted dykes between 1004 and 1061 mbsf (~780 m into basement). It did not quite reach the predicted target depth for the dike-gabbro transition because of lower than expected penetration rates (Fig. 2.4). In October to December of the same year the hole was reoccupied again. Expedition 312 drilled a further 252 m, finally encountering gabbro at 1407 mbsf (1157 m into basement), exactly where predicted from the melt lens depth vs. spreading rate relationship (Wilson *et al.*, 2006).

Figure 2.4 shows that the rate of penetration became very slow towards the base of the sheeted dike complex, corresponding to the level at which extremely tough granoblastic dike material was encountered. It is a significant technical achievement that the crew onboard *D/V JOIDES Resolution* were able to drill through this level and successfully penetrate into the transition zone between upper and lower crust.

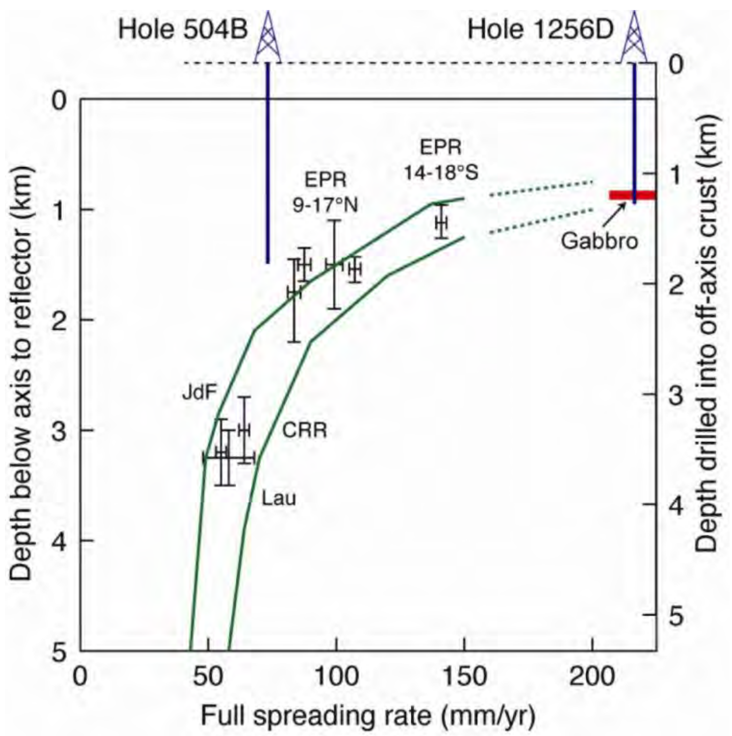


Figure 2.3 Variation of depth to the axial melt lens reflector as a function of spreading rate, extrapolated to the spreading rates encountered at Site 1256. Depth at which gabbro was first intersected in Hole 1256D shown in red (from Wilson et al., 2006).

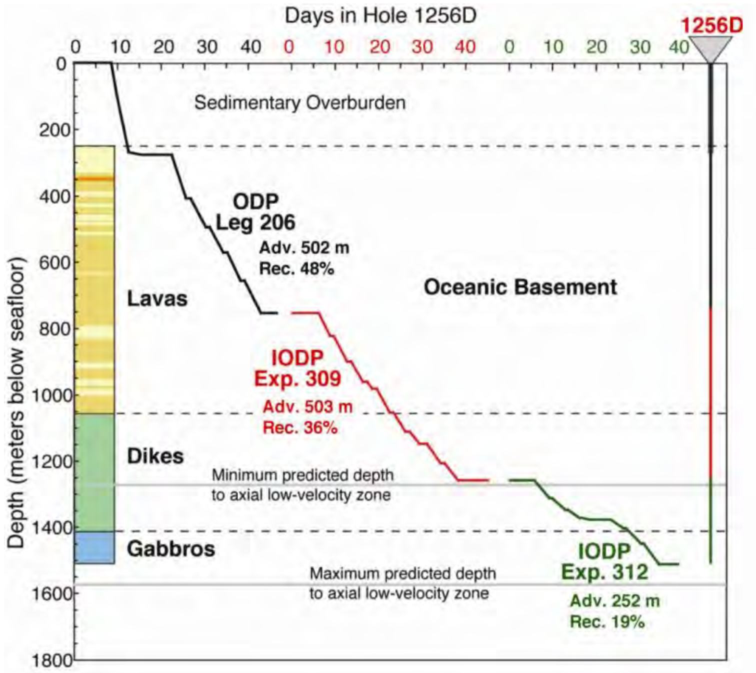


Figure 2.4 Graphic summary of operations at Hole 1256D (from Teagle et al., 2006).

While parts of the post-cruise research is yet to be published, several significant studies are already published or in press within a number of different scientific disciplines. Below, we summarize the main findings and review their importance in relation to the goals of the ISP.

2.2 Achievements

Based upon consideration of the drilling results in conjunction with geophysical studies of mid-ocean ridges and ophiolite studies, a number of first-order advances in our understanding of fast-spread mid-ocean ridge processes are apparent:

Overall crustal structure

Results from Hole 1256D so far are consistent with observations from ophiolites such as Oman in the general relationship of a layered 'Penrose' type crust consisting of an upper crustal sequence comprising extrusive rocks overlying a sheeted dike complex, and a lower crust comprising a plutonic sequence. However, our knowledge of the nature of the lower crust and the mechanisms of its formation has not been significantly advanced from study of the tens of meters of gabbro penetrated thus far. Dikes and gabbros alternate in the lowermost hundred meters of the hole, which probably has therefore probably sampled only the upper part of a sheeted dike-gabbro *transition*, rather than a sharp boundary between the upper and lower oceanic crust (Fig. 2.5). By analogy with seismic evidence and observations from ophiolites (e.g. MacLeod and Rothery, 1992; MacLeod and Yaouancq, 2000), further drilling of even a few hundred meters below the current base of the hole is likely to fully traverse the dike-gabbro transition zone, level of the fossil axial melt lens and penetrate into the uppermost part of the cumulate lower crust. It is only by getting access to these cumulate rocks that we can start to test and/or erect new models for magma chamber processes at fast-spreading ridges and make comparison with similar sections exposed in ophiolites.

That gabbro was encountered at the precise depth predicted from geophysical modeling (Wilson *et al.*, 2003) is a remarkable example of how geophysical studies of active systems such as those pursued in the InterRidge program can be ground-truthed by deep crustal drilling within mature, older crust. The result provides compelling support for the hypothesis that spreading rate is proportional to the depth to the axial melt lens at mid-ocean ridges, and thus for accepted thermal and mechanical models for mid-ocean ridge structure (e.g. Chen and Morgan, 1990; Cannat *et al.*, 2004; Searle and Escartin, 2004).

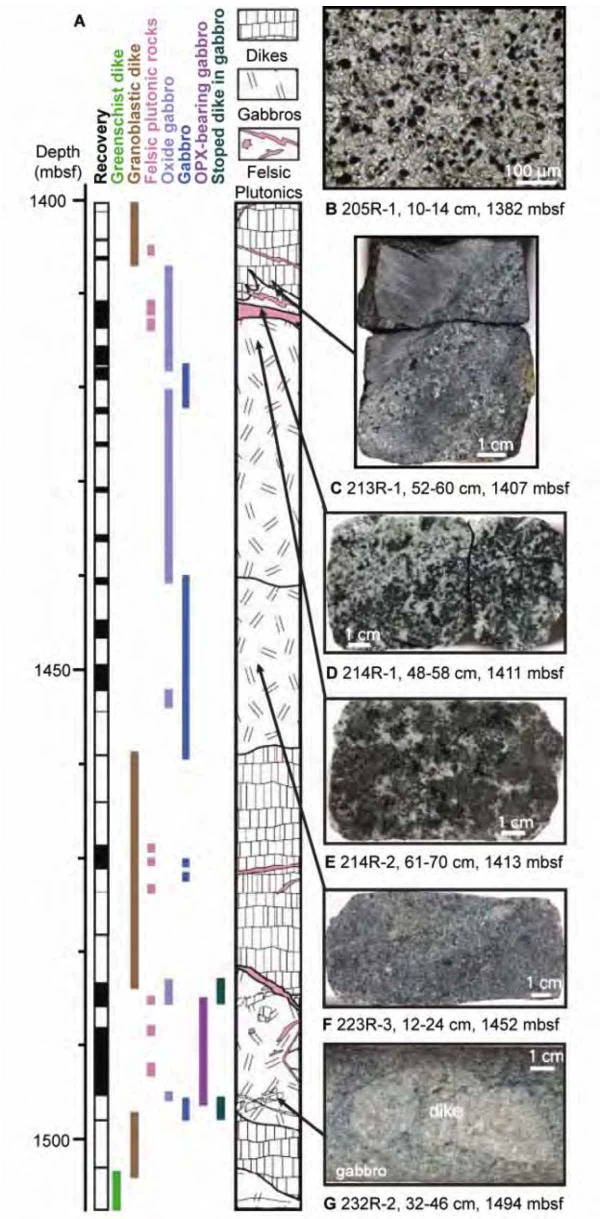


Figure 2.5 [A] Schematic lithostratigraphic section of the plutonic complex from the lower portion of Hole 1256D with representative photographs of key samples. The distribution of rock types is expanded proportionately in zones of incomplete recovery. Felsic plutonic rocks include quartz-rich oxide diorite and trondhjemite. [B] Photomicrograph of a dike completely recrystallized to a granoblastic association of equant secondary plagioclase, clinopyroxene, magnetite, and ilmenite. Some granoblastic dikes have minor orthopyroxene. [C] The dike-gabbro boundary! Medium-grained oxide gabbro is intruded into granoblastically recrystallized dike along an irregular moderately dipping contact. The gabbro is strongly hydrothermally altered. [D] Quartz-rich oxide diorite strongly altered to actinolitic hornblende, secondary plagioclase, epidote, and chlorite. Epidote occurs in ~5 mm clots in the finer grained leucocratic portions of the rock. [E] Disseminated oxide gabbro with patchy texture and cm-scale dark ophitically intergrown clinopyroxene and plagioclase patches separated by irregular, more highly altered leucocratic zones. [F] Medium-grained strongly hydrothermally altered gabbro. The sample is cut by several chlorite and actinolite veins with light gray halos. Plagioclase is replaced by secondary plagioclase and clinopyroxene by amphibole. [G] Clast of partially resorbed dike within gabbro. (from Wilson et al., 2006).

Comparison of the (upper) crustal structure with drilling results from Hole 504B reveals significant differences: the extrusive layer in Hole 1256D is much thicker (~800 m) than the sheeted dike complex (~ 350 m); in Hole 504B the opposite relationship observed (~780 m extrusives and > 1050 m dike complex). Umino *et al.* (2008) propose a magma buoyancy model to explain the unexpectedly thin sheeted dike complex at Hole 1256D (see below); however, submersible observations from the walls of the Hess Deep rift valley suggest that thicknesses of the volcanic and sheeted dike layers in fast-spread crust may be highly variable on a local scale (Francheteau *et al.*, 1992; Karson *et al.*, 2006).

Gabbro was first encountered in Hole 1256D (Fig. 2.5) at a depth a few hundred meters above the best estimate of the depth of the layer 2–3 boundary derived from refraction experiments (Swift *et al.*, 2008). This is apparently the converse of the situation at Hole 504B, in which seismic layer 3 velocities were encountered whilst still within the sheeted dike complex (Swift *et al.*, 1998). These observations support the premise that physical property variations such as porosity play a more important role in controlling bulk velocities and hence layered structure of the ocean crust than do primary lithological changes. This interpretation is also supported by detailed observations within Hole 1256D. Gabbro and trondhjemite dikes intrude into sheeted dikes at 1407 mbsf, marking the top of the plutonic complex. Two major bodies of gabbro were penetrated beneath this contact, with the 52-m-thick upper gabbro separated from the 24-m-thick lower gabbro by a 24 m screen of granoblastic dikes (Fig. 2.5). Porosity increases and P–wave velocities decrease stepwise downward from the lowermost dikes into the uppermost gabbro at Hole 1256D. This likely results from the contact metamorphism and the strong hydrothermal alteration of the uppermost gabbros. Porosity and velocity then increase downhole in the gabbro but are still < 6.5 km s^{-1} (P–wave). The general trends in seismic velocity in holes 504B and 1256D, as well as the detailed trends observed in Hole 1256D therefore both support the premise that porosity/alteration has a strong effect on the seismic velocity, thereby overprinting the effect of the protolith. However, the lowermost lithology encountered in Hole 1256D at the end of Expedition 312 was diabase (Fig. 2.5), and it remains possible that the layer 2–3 boundary may indeed coincide with a final transition at greater depth from sheeted dike complex intro pristine gabbroic lower crust. Even if this was to be the case, Holes 504B and 1256D jointly have delivered a clear demonstration of the limitations of inferring lithostratigraphy from seismic velocity measurements alone. The same conclusion was drawn following the Expeditions 304 & 305 drilling into oceanic core complexes (Chapter 3, this report).

Upper crustal structure

A comprehensive reconstruction of the volcanic stratigraphy of Hole 1256D has been made by Tominaga *et al.* (2009) by combining core observations with downhole geophysical data. Interpretation of electrofacies on borehole wall images obtained from Formation MicroScanner and Ultrasonic Borehole Imager tools in conjunction with neural net classification of downhole petrophysical data has established a well-constrained quantitative physical volcanic stratigraphy. Work in progress (Tominaga and Umino, sub. manuscript) combines this sub-surface stratigraphy together with surface observations from the East Pacific Rise to propose a generic model for the spatial and temporal construction of the extrusive layer at fast- and ultra-fast-spreading ridges.

Umino *et al.* (2008) investigate processes in the sheeted dike complex. Previous conceptual models for the physical structure of the upper oceanic crust (e.g. Ryan, 1994) have proposed the level of neutral buoyancy to be located at the dike-lava boundary, because the bulk density of a Mid-Oceanic Ridge Basalt (MORB) magma is greater than that of the extrusives, but lower than that of the massive sheeted dikes beneath. Umino *et al.* (2008), however, estimate magmastatic and lithostatic pressures for the Hole 1256D section based on core and downhole physical property measurements, and propose that the level of neutral buoyancy was significantly shallower, well within the extrusive section and only a few hundred meters from the original surface. This, they suggest, probably results from the very high proportion of massive sheet flows and relative paucity of pillowed flows within this superfast-spread crust.

Nature of the dike-gabbro transition

The gabbros first encountered at 1407 mbsf in Hole 1256D intrude the sheeted dikes and form at least two discrete sheet-like bodies (Fig. 2.5). Xenoliths of fine-grained diabase in the gabbro show that some of the dike material has been assimilated into the gabbro and partially resorbed as also observed at the dike-gabbro transition in the Troodos ophiolite (Gillis and Coogan, 2002) and in the Oman ophiolite (MacLeod and Rothery, 1992). Dikes have been contact metamorphosed by the gabbro, evident by a granoblastic texture and two-pyroxene assemblage indicating granulite facies conditions ranging from 930°C to 1050°C. Felsic veins of trondhjemitic composition suggest local partial melting of dikes. The very lowermost rocks drilled on Expedition 312 were diabase dikes (Fig. 2.5).

The observations from the base of Hole 1256D show: (1) the boundary between dikes and gabbro is not simple, and (2) Expedition 312 did not drill *through* the dike-gabbro *boundary*, but drilled *into* the dike-gabbro *transition*. If similar to Oman, this transition and the crystallized products of the underlying melt lens could be >100 m thick (e.g. MacLeod and Yaouancq, 2000; Nicolas *et al.*, 2008) before passing down into solid gabbroic cumulate rocks of the lower crust. However, thermal modeling shows that the gabbro intrusions encountered so far are not sufficient to generate the granoblastic contact metamorphism of the lower dikes (Koepke *et al.*, 2008), and a (former) location within a conductive boundary layer above a long-lasting heat source such as a steady-state axial magma chamber, probably tens rather than hundreds of meters below the current base of Hole 1256D, is the most likely initial setting.

Lower crust

Hole 1256D gabbros are slightly internally differentiated, but the intrusive bodies nevertheless are of basaltic bulk composition overall. They cannot therefore be the complementary cumulate residues from an axial magma chamber from which the upper crustal dikes and lavas formed. It follows from here that they are unlikely to represent true lower crust. Instead, it is expected that substantial thicknesses of primitive cumulates must be present somewhere beneath the current base of Hole 1256D. By analogy with relationships in the Oman ophiolite (MacLeod and Yaouancq, 2000), further, moderate deepening of Hole 1256D should recover the upper part of such in situ oceanic lower crust with a few hundred meters of its current total depth.

Crustal magnetization

Previous work pre-drilling had successfully modeled the amplitudes of the marine magnetic anomalies in the area assuming a 500 m layer magnetized at 10 A m^{-1} (Wilson, 1996), though a 1250 m thick layer magnetized at 4 A m^{-1} (for example) would equally explain the data. Average pre-drilling magnetizations in Hole 1256D of 2–5 A m^{-1}, after removing the drill-string overprint, are therefore consistent with the generally held supposition that the upper crustal layer makes the principal contribution to marine magnetic anomalies (Teagle *et al.*, 2006). For further details see Chapter 4.

Thermal history/alteration

Alteration profiles through Hole 1256D reveal an upper crustal (paleo)thermal gradient (~0.5°C m^{-1}) approximately three times higher than that of Hole 504B. This finding is fully consistent with the much shallower depth to the sheeted dike-gabbro transition zone, the relative thin, sheeted dike complex, and the interpretation of an originally very shallow magma chamber. Vigorous convective cooling must have been operating in order to establish such high geothermal gradient. For further details see Chapter 5.

2.3 Conclusions and Recommendations

A number of well documented and important observations were made at Site Hole 1256 during Expeditions 206, 309 and 312:

1) Expedition 312 successfully recovered gabbro below sheeted dikes, but Hole 1256D actually bottomed in diabase. Combined with other observations, it can be concluded that Site 1256 made it into – but not through – the transition zone between sheeted dike complex and a lower gabbroic oceanic crust. This achievement is a 'first' in scientific ocean drilling history.

2) The gabbros recovered on Expedition 312 are in the form of two (probably sill-like) bodies that intrude, and thermally metamorphose, the base of the sheeted dike complex. The amount of heat associated with these bodies does not, however, appear to be sufficient to generate the extent of contact metamorphism observed; hence a much larger body of gabbro – probably the axial melt lens – is thought to be present very close to the current base of Hole 1256D.

3) The bulk composition of the gabbro bodies is similar overall to that of the dikes and overlying lavas. It is therefore not representative of the type of cumulate gabbro expected to make up the lower oceanic crust. Based on comparisons with ophiolite studies more primitive cumulate gabbros can be expected to be present no more than a few hundred meters below.

4) Surface seismic data indicates that the seismic layer 2/3 boundary is located near the bottom of Hole 1256D. Taking into account that seismic resolution at these depths and (high) seismic velocities has inherent error bars in the vertical range of hundred of meters, the layer 2/3 boundary is expected to occur within a maximum of a few hundred meters below the bottom of Hole 1256D. Seismic velocities measured on the core did not show a transition to seismic layer 3 velocities within the gabbros recovered. However, the possibility that the seismic layer 2/3 boundary at Site 1256

coincides with the (full) transition into in situ gabbroic lower oceanic crust therefore still exists.

5) The relatively thin (1180 m) upper oceanic (igneous) crust is partitioned into a relatively thick extrusive sequence (800 m) and a very thin (380 m) sheeted dike complex suggesting a shallow crustal position of the former magma chamber. Consistent with this, the observed alteration pattern indicates a very high (paleo)geothermal gradient, likely supported by vigorous convective cooling. The relatively thick extrusive carapace must have avoided dike injection through rapid lateral transport away from the (narrow?) zone of dike injection, possibly by a combination of ridge morphology and initial flow distribution, superfast spreading and well focused dike injection from the shallow magma chamber.

6) A high proportion of quite massive, in part thick, lava flows, and a scarcity of pillow lavas is observed. This may have elevated the level of neutral buoyancy of the intrusive magma.

One of the most prominent initiatives of the IODP Initial Science Plan is the '21st Century Mohole', which aimed "*to advance significantly our understanding of the processes governing the formation and evolution of oceanic crust*" by planning to "*recover a complete section of oceanic crust and uppermost mantle generated at a fast-spreading ridge*" (International Working Group, 2001). This ambitious goal will not have been met during the lifetime of the current IODP, lack of a deep-water (4000 m) riser capability being one factor. However, in lieu of this very ambitious goal, operations that commenced just before the end of ODP (Leg 206) and continued during two expeditions (309 and 312) in phase 1 of IODP have made significant progress towards the objective of understanding "*processes governing the formation and evolution of oceanic crust*" in a fast-spread setting. Furthermore, the operations so far at Hole 1256D – which is open and ready for deepening by non-riser drilling – have left the program uniquely poised to make even more fundamental advances in our understanding of magmatic accretion processes at mid-ocean ridges by returning to the hole and penetrating through the dike-gabbro transition into plutonic rocks from the axial melt lens and underlying cumulate pile. Recovery of the seismic layer 2/3 boundary in the core itself would be another significant achievement ground-truthing a first order seismic boundary within in situ oceanic crust.

The overall scientific achievement of operations at Site 1256 should already be viewed as one of the main highlights of the current phase of IODP. Deepening of Hole 1256D before end of the current phase of IODP will likely generate scientific results of even greater long-term impact.

3. Studies of Slow-Spread Crust

3.1 Introduction

Slow- and ultra-slow spreading centers generate crust that seems markedly heterogeneous on a variety of scales, suggesting that profound variations in magmatic and tectonic activity operate along these spreading ridges. Tectonic processes must supplement magmatic processes in accommodating extension along the divergent plate boundary. Tectonically dismembered, slow-spread crust allows for an 'offset drilling' strategy, by which sections of the crust composed of rocks exhumed from greater depth along normal faults can be sampled by moderate drilling penetration (100 m – 1000 m scale). However, it is becoming increasingly clearer that these deep windows into the crust may not represent similar, deep but not exhumed entities from more fast-spread crust. They likely are unique to this type of crust.

Results from the studies of the Mid-Atlantic Ridge (MAR) during ODP Leg 209 and IODP Expeditions 304 & 305 show that crust generated at slow- spreading centers is heterogeneous and complex; furthermore, they pose questions about the geological meaning of the geophysically defined crust and mantle in these settings. Below, we review results from the two different regions studied on the MAR: at 15°N (ODP Leg 209) and 30°N (IODP Expeditions 304 & 305).

3.2 Achievements – Slow-Spread Crust in the Central Atlantic

Fifteen–Twenty Fracture Zone

ODP Leg 209 aimed to drill shallow holes into mantle peridotite along the MAR from 14° to 16°N in order to sample the upper mantle (now incorporated into the lithosphere) in a magma-starved portion of a slow spreading ridge. The location was favored because igneous crust per se (gabbro, diabase, basalts) was known from submersible studies to be locally absent. It was therefore surmised that along-strike variations in mantle structure and composition could be evaluated by drilling a series of shallow holes along an approximately 100 km-long section of the Mid-Atlantic Ridge either side of the Fifteen-Twenty fracture zone (Fig. 3.1).

The primary aim of Leg 209 was to examine variations in mantle deformation, composition, melt migration features, and alteration from ridge center to ridge end to test the hypothesis that mantle flow and melt extraction along slow spreading ridges might be focused at the centers of ridge segments. During this expedition 19 holes were drilled at eight different sites north and south of the 15°20' N Fracture Zone (Fig. 3.1). Despite the drill sites being located close to known peridotite or gabbroic outcrops, two sites (Sites 1269 and 1273) encountered only basaltic rubble. The six other sites, however, yielded complex assemblages of serpentinized peridotite and gabbroic rocks. Coring at Sites 1268, 1270, 1271, and 1272 recovered ~25% gabbroic rocks, commonly intrusive into the host peridotite. The distribution of gabbro and peridotite is illustrated

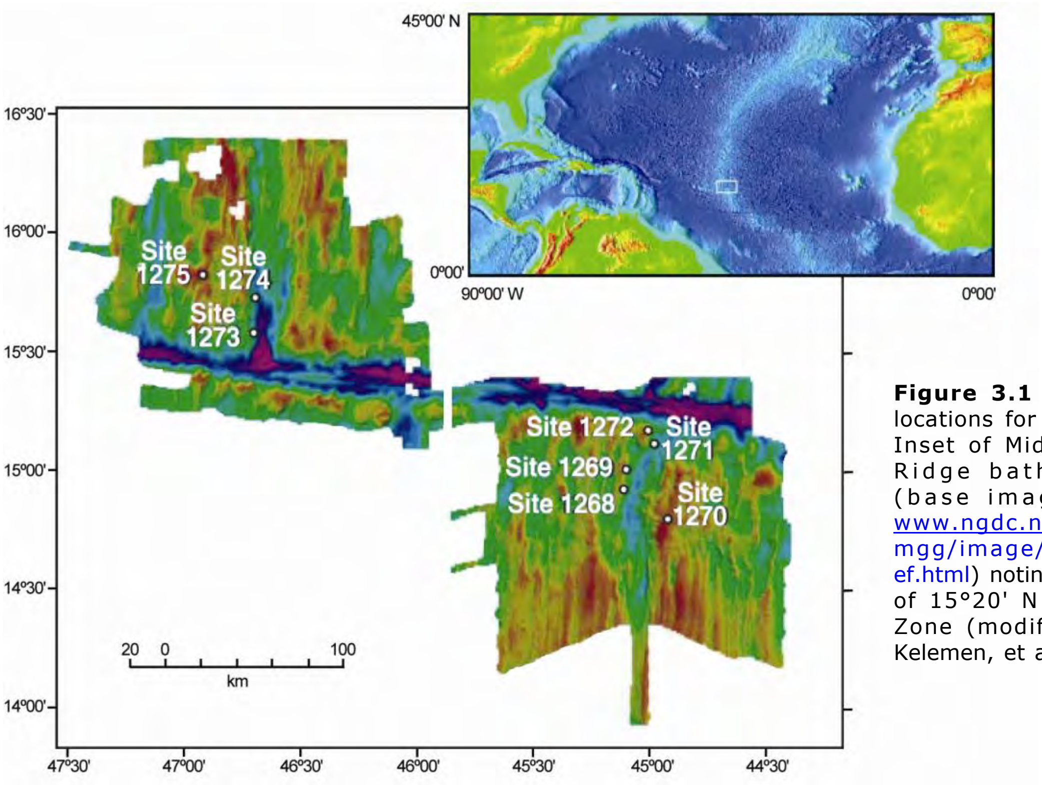


Figure 3.1 Drill site locations for Leg 209. Inset of Mid-Atlantic Ridge bathymetry (base image from www.ngdc.noaa.gov/mgg/image/2minrelief.html) noting location of 15°20' N Fracture Zone (modified from Kelemen, et al., 2004).

in schematic core logs in Fig. 3.2 and shows the variation from site to site. End members are Site 1274, which is essentially all serpentinized peridotite with rare, meter-thick gabbroic layers or lenses, and Site 1275 which is predominantly gabbro with less abundant troctolitic rocks. These troctolites are interpreted to form from a peridotite protolith infiltrated along grain boundaries by gabbroic melt.

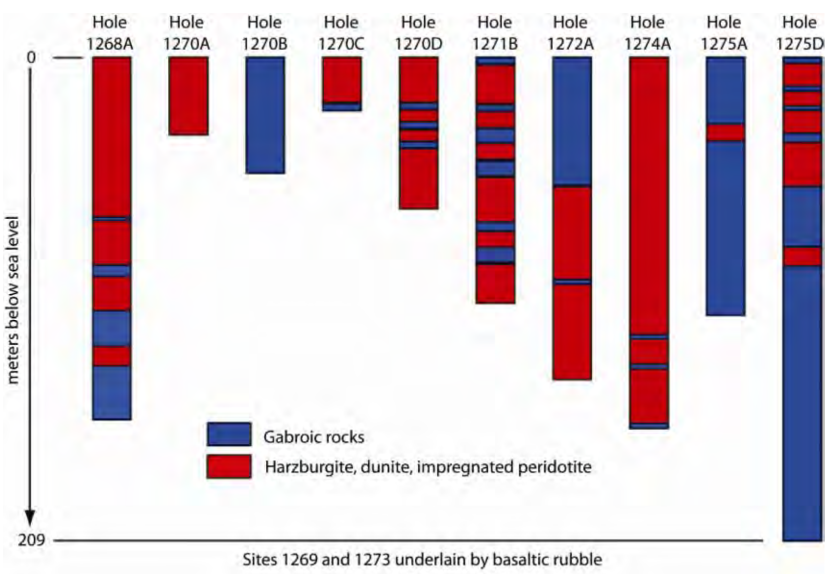


Figure 3.2 Simplified core logs for Sites 1268, 1270, 1271, 1272, 1274, and 1275 (detailed lithologic sections are available in: Shipboard Scientific Party, 2004: figs. F7, F21, F31, F37, F42, F50). Based on these data, we infer that the entire area may be underlain by mantle peridotite with ~20% – 40% gabbroic intrusions and impregnations, consistent with results of previous dredging and submersible studies (after Kelemen, et al., 2007).

The primary conclusions from this drilling effort were: (1) that mantle deformation fabrics are ubiquitously weak except where localized along high temperature shear zones; and (2) that significant proportions of gabbroic rocks intruded the peridotite at locations both near and far from the Fifteen-Twenty fracture zone, although other locations both proximal and distal to the fracture zone yielded no evidence of gabbroic intrusion.

The hypothesis that distribution of melt is focused toward the centers of ridge segments is therefore not supported by the observations from Leg 209. Likewise, evidence for focused mantle upwelling was not found. Instead, results suggest that upwelling mantle beneath the slow-spreading ocean crust – at least in the 15°N region – does not undergo penetrative deformation as a result of plate spreading, but instead rises passively to the base of the thermal boundary layer beneath the ridge and is incorporated into the lithosphere (Fig. 3.3). In this model, motion instead takes place along localized shear zones in the cold lithosphere.

The peridotites recovered by Leg 209 show locally abundant impregnated peridotite, suggesting that significant interaction with migrating intergranular melt took place. These intergranular melts were at or near equilibrium with the mantle they intruded, and seem not to have coalesced into discrete channels of migrating melts. This contrasts with observations made in many ophiolites, in which dunite conduits are common. Such dunites are inferred to be the highly focused channelways of melts that ascend to feed the overlying igneous crust, and their apparent absence in the 15°N region may suggest

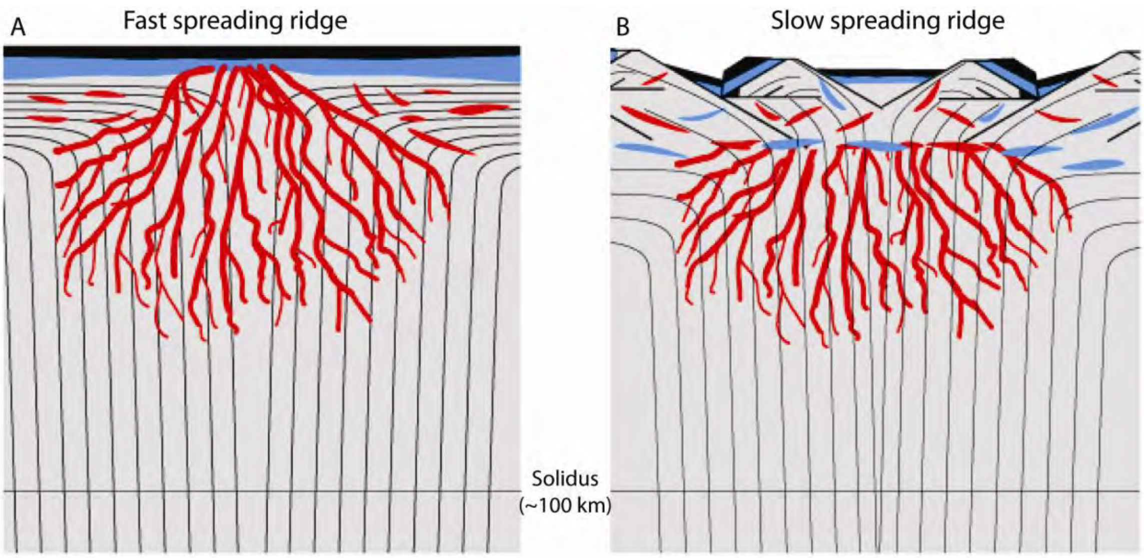


Figure 3.3 Synoptic diagram illustrating the inferred difference between igneous accretion and seafloor spreading at fast- vs. slow-spreading ridges. [A] Impregnated peridotites and gabbroic plutons are rare in the sub-500 m mantle section of the Oman ophiolite and the shallow mantle shows penetrative ductile deformation of residual peridotites as a result of plate divergence (Kelemen et al., 2000). We infer that this represents a medium- to fast-spreading ridge, where astenospheric mantle flow extents upwards to close to the base of the igneous crust. [B] A hypothetical end-member scenario for igneous accretion and seafloor spreading at a slow-spreading ridge. Impregnated peridotites and gabbroic plutons begin to form at the base of the mechanically rigid lithospheric lid, >15 km below the seafloor. Plate spreading in the upper rigid and non convecting mantle (e.g. lithosphere) is accommodated by localized deformation along mylonitic shear zones and—at lower temperatures—brittle faults. These shear zones and faults rotate and uplift passive blocks of residual peridotite that host gabbroic intrusions. Modified from Kelemen et al., 2007.

that focused melt transport along mantle-hosted conduits was not a major contributor to the evolution of ocean crust in this slow-spreading environment, perhaps contributing to the lack of development of any significant extrusive carapace.

Finally the observation of relatively abundant gabbro (~25-30%) in Leg 209 cores challenges the concept that the ocean crust north and south of the Fifteen-Twenty Fracture Zone is amagmatic. Instead it supports a hypothesis in which the lack of a continuous magmatic ocean crustal layer is at least partly offset, in terms of melt volume, by a high proportion of gabbroic magma trapped in the lithosphere at depth. This crystallized as intrusions within a mantle protolith that had already suffered melt impregnation itself.

Atlantis Massif

Oceanographic studies and drilling within the Atlantic and Indian oceans of slow-spread ridges prior to IODP Expeditions 304 & 305 (ODP Legs 118, 153, 176, 179 and 209) indicated that lower crustal and upper mantle sequences, often forming dome-shaped topographic highs, are exposed close to the ends of ridge segments bounded by transform faults. Referred to as oceanic core complexes (OCCs), these topographic highs are believed to be associated with long-lived normal faults (detachment faults) that have contributed to accommodate extension in relation to plate divergence.

IODP Expeditions 304 and 305 targeted the 1.5 to 2 Myr old dome-like Atlantis Massif, located just west of the MAR at 30° N. The massif forms the inside corner of the intersection between the MAR and the Atlantis Transform Fault (Fig. 3.4) and is interpreted as an oceanic core complex (OCC) comprised of lower crustal and upper

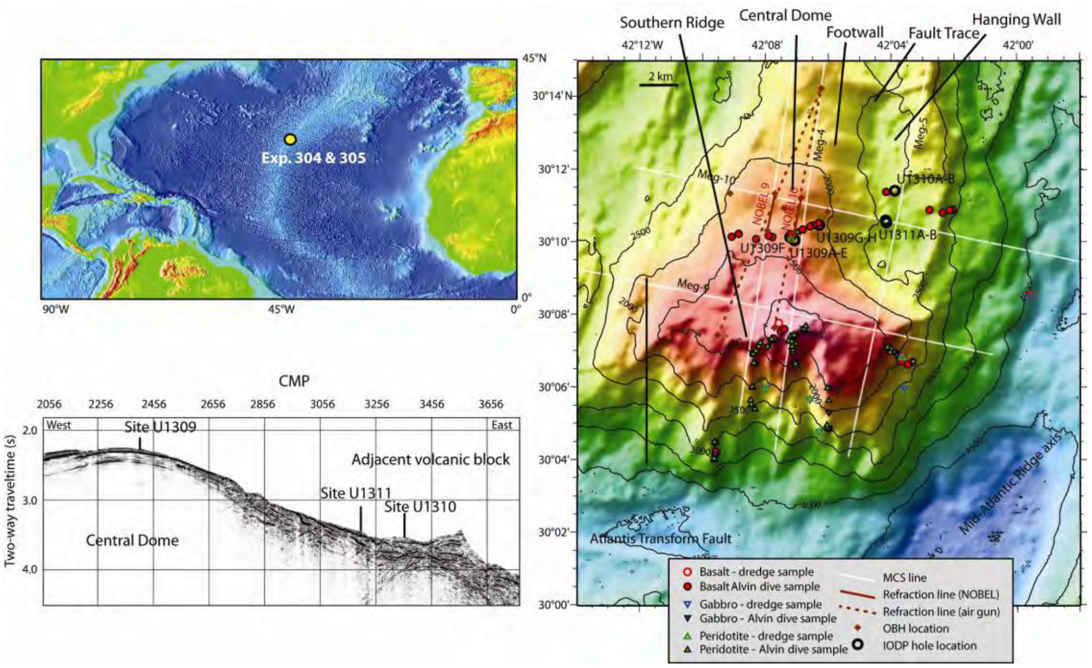


Figure 3.4 Regional setting of the Atlantis Massif and IODP Hole U1309D. [A] Location of Expeditions 304 and 305. [B] Base map showing prior geological and geophysical data coverage and IODP drill sites (circles). [C] Bathymetric contours illustrate the deep median valley of the Mid-Atlantic Ridge and its intersection with the Atlantis transform fault. The shallow, corrugated dome has two structural components: the central dome and the Southern Ridge. The eastern block is basaltic and is interpreted as the hanging wall (after Ildefonse et al., 2006).

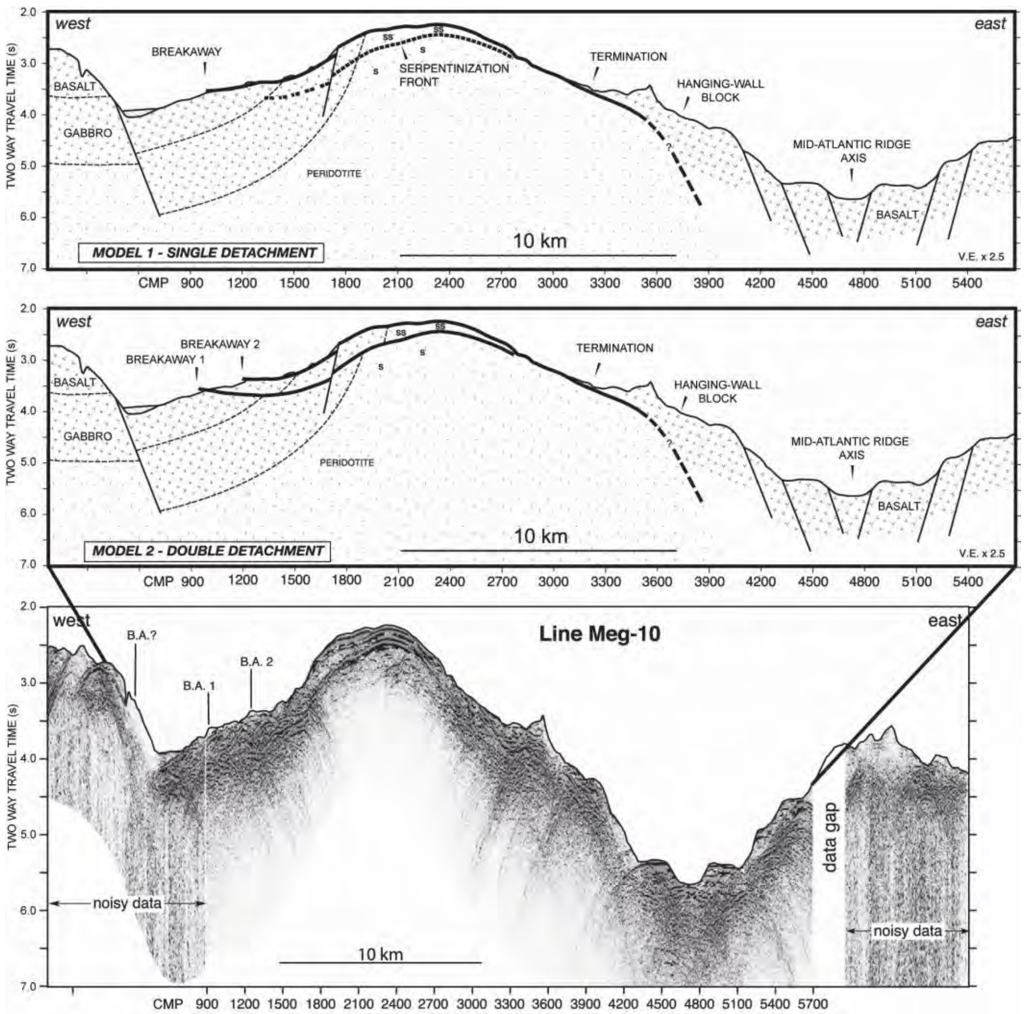


Figure 3.5 Interpretation of multi-channel seismic reflection data across the Atlantis Massif (from Canales et al., 2004). A strong reflector is visible at 0.2–0.5 s below much of the domal surface and coincides roughly with the depth below which mantle velocities were inferred from the seismic refraction data. The "D reflector" was interpreted pre-drilling to possibly mars an alteration front within the peridotite-dominated massif.

mantle rocks. Three domains are distinguished on the basis of lithology and morphology: a central dome, a peridotite-dominated southern wall and a basaltic eastern block, interpreted as a hanging wall separated from the OCC by a detachment fault (Figs. 3.4 and 3.5). Side-scan sonar data indicate a distinct corrugated upper surface on the top of the massif, which has been interpreted as the fault-plane of the detachment responsible for the widespread exposure of lower crustal and upper mantle rocks (Blackman *et al.*, 2002).

The key goals of the IODP expeditions were to: (1) verify the presence and nature of the detachment fault system, and its role in OCC formation (Fig. 3.6); and (2) by deep basement drilling into the detachment footwall attempt to penetrate the high seismic velocities (8 km s^{-1}) believed to lie at depths <1 km below seafloor and which were interpreted to be potentially composed of fresh mantle peridotite. The high velocities were approximately co-located with a strong reflector seen in refection seismic data (Fig. 3.5; Canales et al., 2004), and a positive gravity anomaly that exists across the whole central dome (Blackman *et al.*, 2002).

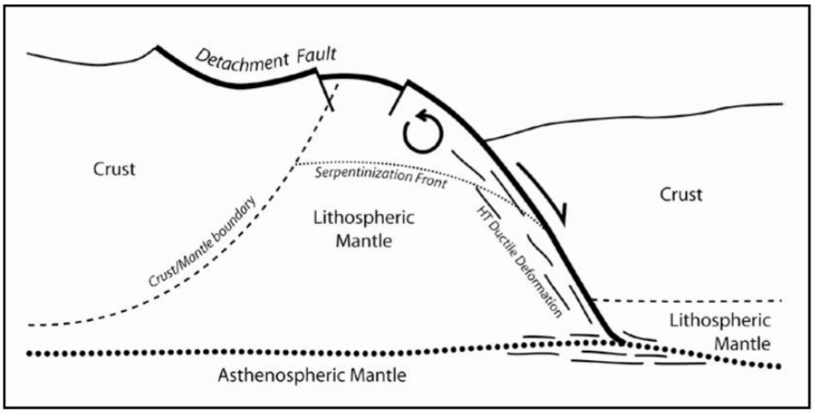


Figure 3.6 Schematic cross-section of the rolling hinge model for oceanic core complex evolution (after IODP Expeditions 304 and 305 Scientists, 2005).

The inferred transition to 8 km s^{-1} velocities and seismic reflection at around 800 mbsf on the surface of Atlantis Massif was by far the shallowest place the seismic Moho had been recognized in the oceans and hence offered a unique opportunity to drill the true seismic Moho. Because of the known outcrops of peridotite in the vicinity the transition was interpreted pre-drilling as representing a possible serpentinization front (i.e. a Hess-type ocean crust model) below which mantle peridotite would be present.

Relatively shallow sites were planned for the hanging wall in order to recover volcanic rocks above the hypothesized detachment fault and the fault zone itself. A >800 m deep hole near the crest of the OCC was planned to test the Hess type serpentinization model (Fig. 3.6). In support of the latter, abundant site characterization, in particular along the southern wall, by dredging and sampling from submersible had shown outcrops of serpentinite and talc schists including the famous 'Lost City' venting area (Fig. 3.7) interpreted to be fueled by deep and extensive serpentinization (Blackman *et al.*, 2002; Kelley *et al.*, 2001; Kelley *et al.*, 2005).

Thwarted by difficulties of establishing stable holes in young volcanic rocks, drilling in the hanging wall (Sites U1310 and 1311) was not able to provide any significant penetration and recover the target of the presumed detachment fault at depth. Drilling only recovered small fragments of basaltic rock, although, significantly, it confirmed the assumed nature of the hanging wall and confirmed the overall tectonic model for the Atlantis Massif (Cann *et al.*, 1997).

Drilling in the footwall on the crest of the dome, however, was operationally very successful. Site U1309, located at 1650 m water depth on the crest of the central dome, consists of two deep holes (Holes U1309D, main hole; and Hole U1309B, pilot hole) and five shallow penetration holes (Hole U1309A and Holes U1309E–H). The main Hole U1309D at a water depth of 1656 m penetrated 1415.5 mbsf with an average core recovery 75%. Quite unexpectedly, the predominant lithology recovered was gabbroic rocks (91.4%) with minor intercalated ultramafic rocks (5.7%) and diabase (~3%) (Fig. 3.8). The gabbroic rocks are compositionally diverse and comprise gabbro, olivine gabbro/troctolitic gabbro, troctolite, and oxide gabbro. A series of olivine-rich rocks (~5%; dunites, wehrlites, troctolites), grouped as olivine-rich troctolites, part of which likely represent primitive cumulates, are interlayer with gabbroic rocks. Mantle peridotites are very rare (<0.3%) and are concentrated in the upper part of Hole

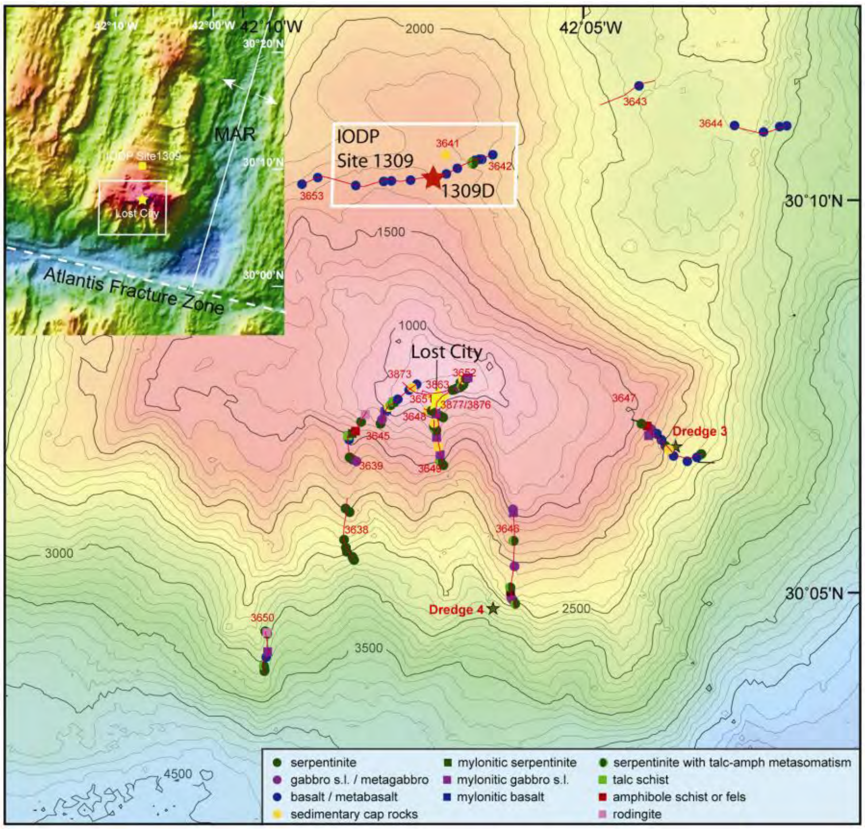


Figure 3.7 Bathymetric map of the southern and central portions of the Atlantis Massif showing the location of the Lost City Hydrothermal Field and IODP Site U1309 in relation to Alvin dive tracks (in red) and lithologies determined by submersible sampling completed during the 2000 (MARVEL cruise; dives 3639 through 3652; Blackman et al., 2002) and 2003 field campaigns (dives 3862 through 3881; Kelley et al., 2005; Karson et al., 2006). Dense locations of Alvin dives around the Lost City conducted in 2003 have been omitted for clarity. Inset shows location of the massif and local plate boundaries (Compilation courtesy of G. Früh-Green).

U1309D (<225 m). The igneous rocks recovered from the hole are the most primitive ever cored in slow-spreading ocean lithosphere (with high Mg# (74–90), low TiO_2 (<0.49 wt%) and Na_2O (0.1–3.7 wt%).

Within the seemingly large number of discrete igneous units present in the drill core, detailed petrological analyses and age-dating show the presence of 'macro-units' that are hundreds of meters thick and represent at least two periods of magmatic activity separated by ~70 ka (Fig. 3.8; Suhr *et al.*, 2008). Each 'macro-unit' represents repeated intrusive events with a calculated average intrusive pulse of the order of ~20–40 ka, consistent with core observations that show significant complexity on a smaller (10 m) scale (Grimes, *et al.*, 2008).

The almost complete absence in the drill core of serpentinite, the predominant occurrence of gabbro and the very limited occurrence of mantle peridotite (mainly in the upper part of the hole) are all at significant odds with previous field studies (Blackman *et al.*, 2002; Kelley *et al*., 2001; Karson *et al*., 2006) and the pre-drilling hypothesis that a transition should occur at ~800 m depth from serpentinized mantle peridotite to un-altered, or nearly fresh, mantle peridotite. Furthermore, no seismic P-wave velocities as high as 8 km s^{-1} were found in the cores themselves or in downhole logging data, contradicting the predictions from modeling of the seismic wide-angle data.

Regarding the pre-drilling site characterization, the review panel concluded that the seismic data were not interpreted fully prior to drilling. Also, the pre-drilling gravity model had degrees of freedom that made it no more than indicative. Post-drilling refinements of the gravity model based on drilling data, however, show a good fit (Blackman *et al.*, 2006), and re-interpretation of seismic data also have removed much

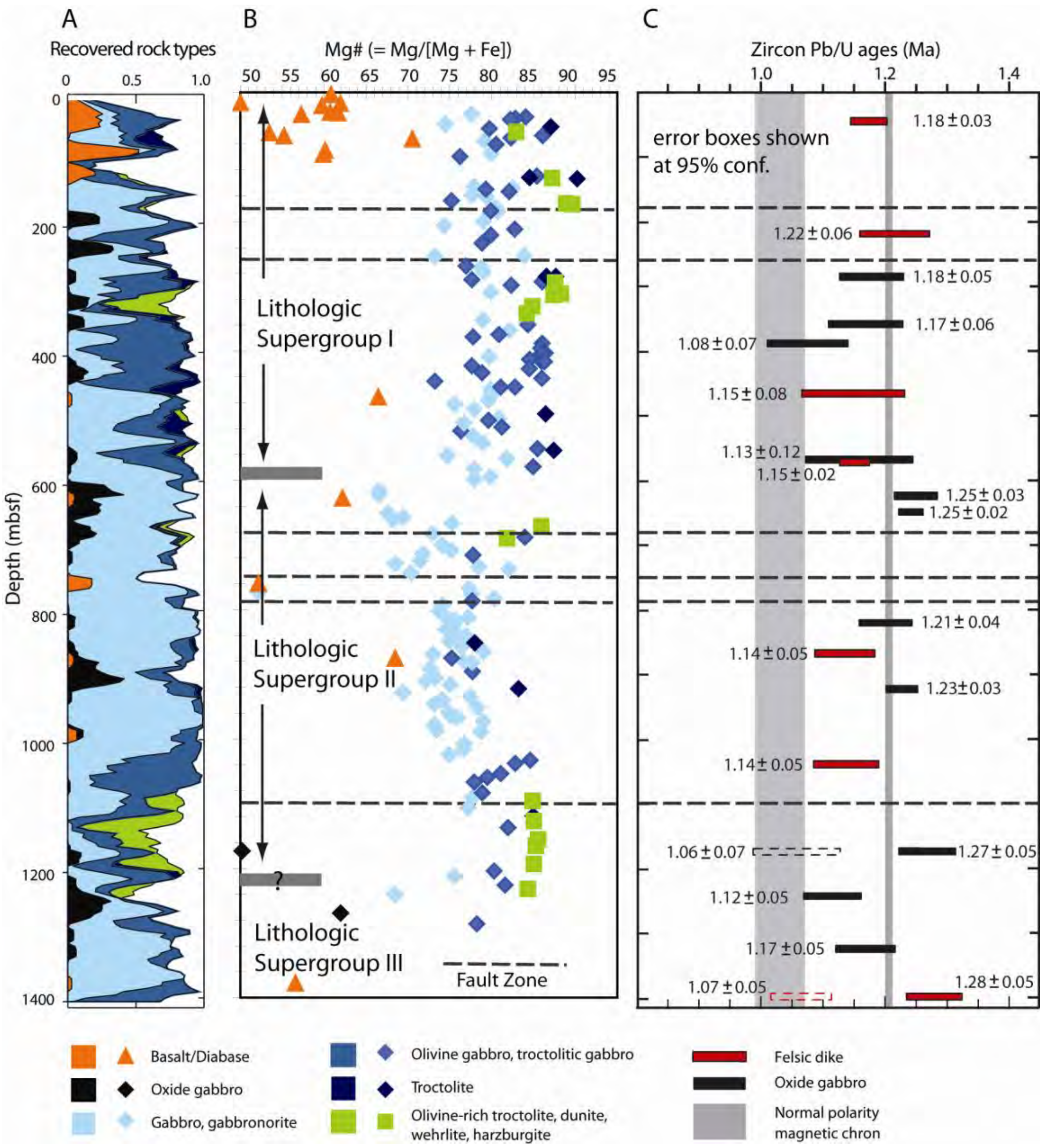


Figure 3.8 Plots of depth versus [A] average of rock type recovered in Hole U1309D, [B] whole-rock Mg#, along with inferred lithologic supergroups and fault zones (Blackman et al., 2006), [C] 207Pb and 230Th corrected 206Pb/238U sample weighted average zircon ages (shaded fields represent the Jarmillo and Cobb Mountain normal polarity intervals) (based on Grimes et al., 2008).

of the inconsistency with the borehole observations (Blackman, *et al.*, 2008; Collins *et al.*, 2009). While the pre-drilling seabed sampling program was quite extensive and had been considered fully adequate by the IODP Site Survey Panel, the fact that it failed to indicate the presence of a massive gabbro body at the site of drilling demonstrates the limitations of seabed sampling programs in complex settings (e.g., Blackman *et al.*, 2002; Karson *et al.*, 2006). Future site surveys in similar settings might consider, for example, shallow (m to 10s of m scale) coring prior to deep drilling (e.g. MacLeod *et al.*, 2002). An improved surface sampling program is also highly recommended as a post-drilling effort. This would be able to provide much needed 3-dimensional control of the extent of the previously unsuspected gabbro body, which is now proven to be a minimum of 1.4 km thick at Hole U1309D. Recent reprocessing and reassessment of the available geophysical data in three dimensions, utilizing the velocities measured in the borehole wall and cores, is allowing the extent of the gabbro body to be assessed (Blackman, *et al.*, 2008; Collins *et al.*, 2009).

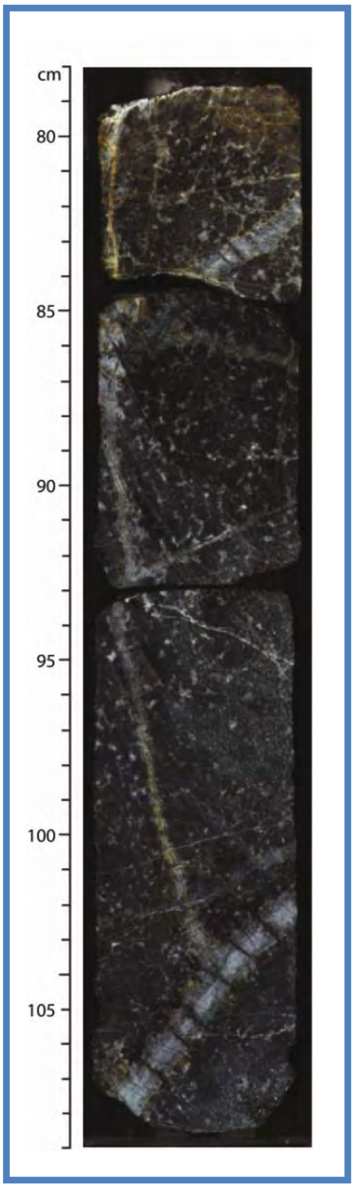
3.3 Summary and Conclusions – Slow-Spread Crust

ODP-IODP drilling during ODP Leg 209 and IODP Expeditions 304 & 305 has resulted in some significant surprises, not least the recovery of gabbro instead of the predicted mantle peridotite at Site U1309. On one level this amply demonstrates the continued need for drilling to ground-truth deductions based on geophysics. The operations overturned many pre-drilling hypotheses and demonstrated a previously unrecognized complexity in the processes of ocean lithosphere in slow-spreading environments. They support the rolling-hinge detachment fault model (see Section 4 below), suggest a revision of the paradigm regarding magma generation and distribution within slow-spread crust, and possibly also for the entire mechanism of crustal formation within this environment. The success of these studies to a large extent results from the good to excellent core recovery in particular in the impressive 1.4 km deep basement Hole U1309D, which has allowed for detailed studies of magnetic properties (reorient cores through comparison with borehole wall images) and geochronology at an unprecedented resolution. In the following, we summarize some key findings that have furthered our understanding of the formation of oceanic lithosphere at slow-spreading ridges as a result of drilling:

1) Melt-mantle interactions documented during ODP Leg 209 confirm that a significant volume of melt does not leave the mantle host rock. Instead, mantle rocks now forming the ‘crust’ (seismically, P-wave velocity lowered by several processes, including serpentinization and fracturing) have been shown to contain a variety of intrusions. These show chemical interactions between the host peridotite and intrusive melts. In addition, widespread melt impregnation, interpreted to reflect flow of melt along grain boundaries within the mantle protolith, can be documented. Less conclusively, drilling results may also suggest that porous flow channels representing melt migration from the zone of melt production to magma chambers existed.

2) The discovery of a very large gabbro body during IODP Expeditions 304 & 305, most likely intruded into a mantle host, suggests that the Leg 209 findings of melt entrapment in the mantle is representative for larger areas, and secondly that the volume of melt trapped in the mantle lithosphere indeed can be very significant. The results from Leg 209 and Expeditions 304 & 305 fundamentally challenge the widespread notion that melt generated by decompression melting of the rising asthenosphere below mid-ocean ridges leaves the mantle to form a continuous magmatic crustal layer, either in the lower crust (gabbro) or upper crust (dikes and lavas). Also at odds with conventional thinking is that the drilling results show that primary melts extracted from the asthenospheric mantle react with cooler lithospheric mantle, thereby significantly altering the composition of the melts as well the mantle host rocks (Fig. 3.9). Finally, the drilling results seriously call into question the concept of ‘amagmatic’ ridge segments at slow- and ultra-slow-spreading ridges: melt may in

Figure 3.9 Close-up photograph of troctolite, interpreted as impregnated peridotite, cut by altered gabbroic veins (interval 209–1275D–9R–1, 79–109 cm) (from Shipboard Scientific Party, 2004).



fact still be generated by decompression melting, but can simply be trapped within the mantle host and not form an igneous crustal layer at the surface.

3) The presence of a large detachment fault responsible for the exposure of the Atlantis Massif is strongly supported by drilling, though, unfortunately was not recovered in situ. Attempts to constrain the rotation history of footwall of the detachment fault system using paleomagnetic data are consistent with the rolling hinge detachment fault model (Buck, 1988). In particular, integration of core and borehole wall images from Hole U1309D has allowed limited reorientation of drill core and hence of paleomagnetic data, from which the rotation history can be more reliably constrained (see Section 4 below). These results are consistent with new geophysical constraints on the geometry of axial detachment faults at depth (deMartin *et al.*, 2007).

4) Another important finding made possible by the high recovery core from Hole U1309D is the detailed U-Pb dating of zircons in the gabbro body drilled at this site (Grimes *et al.*, 2008). This chronology reveals the protracted 'near-axis' construction of the magmatic system by successive gabbroic intrusions over about 200,000 years within the footwall of the axial detachment fault system, probably at a range of depths. Following on from this result is the confirmation, particularly from the study of olivine-rich cumulates at Site U1309, that the composition of slow-spreading ridge gabbros does not result solely from fractional crystallization, but is also in part determined by subsequent chemical interactions between new incoming melts and preexisting cumulates. These findings call for a new generation of petrogenetic models for oceanic gabbros.

5) The bulk composition of the gabbroic sequence drilled at Site U1309 (Atlantis Massif) is markedly more primitive than that drilled at Site 735 (Southwest Indian Ridge, ODP Legs 118 and 176). Interestingly, however, the bulk chemistry of the 'primitive' cumulates at Site U1309 is still too evolved to balance the composition of mid oceanic ridges basalts according to conventional petrogenetic models. This suggests that the most primitive melts may be concealed somewhere else. In addition, the significant volumes of fractionated gabbros that have now been drilled at three slow-spreading ridge locations (Atlantis Massif during Expeditions 304–305, 15°45′N [Site 1275] during Leg 209, and Atlantis Bank during Legs 118 and 176) indicate that these gabbroic sequences represent melt bodies that crystallized at depth within the lithosphere, and which did not necessarily feed extensive volumes of erupted lava.

6) Most exhumed rocks (gabbros and ultramafics) at all drill sites lack a lithospheric deformation imprint, and fault rocks, despite poor recovery, are comprised of talc-

schist, amphibolites and serpentinites. Together, these findings challenge the commonly held hypothesis that the bulk rheology of slow-spread lithosphere is uniquely controlled by temperature, and indicate instead that strain localization mechanisms favored by lithological contrasts and hydrous alteration also play an important role.

4. Magnetization of the Crust

4.1 Introduction

Studies of magnetization of the ocean crust have two major goals. The first goal is to assess the roles of different rock types that make up the upper oceanic crust in generating marine magnetic anomalies. The Initial Science Plan states that the source of marine magnetic anomalies will be much better understood when a complete section of the lower oceanic crust is available for analysis. Further, one of the goals of IODP Expeditions 309 & 312 was to correlate and calibrate remote geophysical seismic and magnetic imaging of the structure of the crust with basic geological observations (Alt *et al.*, 2007). The second goal is to aid structural analysis by providing information on piece orientation, because paleomagnetic remanences are useful information as markers for tectonic rotation.

It is worth to note that magnetization studies have technical limitations. Almost all ODP and IODP core samples have a pronounced drilling overprint, which is characterized by a steep downward direction and a radial-horizontal component that points toward the center of the core. Removing the overprint either by alternating-field or thermal demagnetization is essential to isolate the original magnetization (Fig. 4.1), although recent experiments have shown that it may be impossible to remove the drillstring overprint completely (Morris *et al.*, sub. manuscript). Even with successful isolation of the primary magnetization, however, only the inclination of the remanence direction is normally retrieved, because the azimuthal orientation of the sample is generally unknown and the declination cannot therefore be determined. Furthermore, the drilling overprint results in difficulty in estimating the intensity of the pre-drilling magnetization. Integration of sample measurements with measurements of the magnetic field in the borehole should allow progress in characterizing the crustal magnetization.

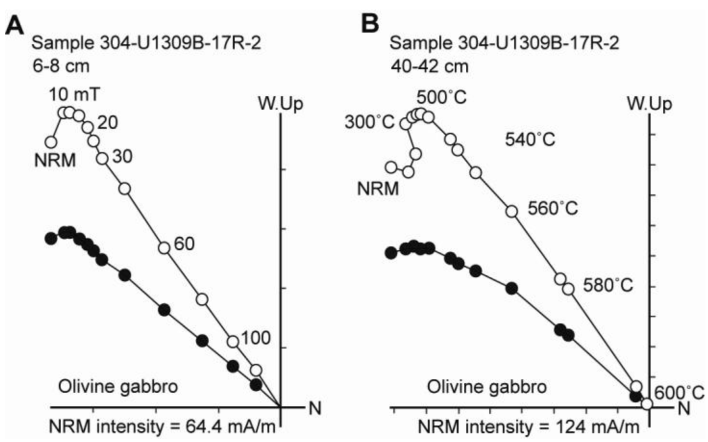


Figure 4.1 An example for removal of pronounced drilling overprint using alternating-field and thermal demagnetization. Representative vector endpoint diagrams for discrete samples with well-defined reversed polarity components. Open circles – projections of the remanence onto the north-south vertical plane, solid circles – projections of the remanence onto the horizontal plane. NRM – natural remanent magnetization (after Blackman et al., 2006).

4.2 Source of Marine Magnetic Anomalies

The source of marine magnetic anomalies was only investigated using cores from the fast-spread crust at Hole 1256D, (Teagle *et al.*, 2006). The amplitude of the marine magnetic anomalies in the area of Site 1256 has been satisfactorily modeled by Wilson (1996) with a layer 500 m thick magnetized at 10 A m^{-1}. A layer 1250 m thick with a magnetization of 4 A m^{-1} would, of course, produce an equivalent anomaly. An average 'pre-drilling magnetization' of 2–5 A m^{-1} is within the plausible range for the dikes and gabbros recovered at Site 1256, so they remain candidates for a significant fraction of the source of marine magnetic anomalies. The progress in estimating the pre-drilling magnetization is important for the further study with overcoming technical limitations (e.g. a pronounced drilling overprint of core samples), which can be achieved through an integration of sample measurements with measurements of the magnetic field in the borehole.

4.3 Information to Aid Structural Analysis

Knowledge of the direction of the pre-drilling magnetization is essential if quantitative estimates are to be made of the axes and magnitudes of tectonic rotation since the magnetization was acquired. The rolling hinge model for oceanic core complex evolution (e.g. Tucholke *et al.*, 1997; Escartin *et al.*, 2003; see Fig. 3.6) can potentially be tested using paleomagnetism. One assumption in the use of paleomagnetic data to document tectonic rotation angle is the requirement that the magnetization was acquired over sufficient time (~10^3–10^4 yr) to average secular variation so that the initial magnetization coincides with the time-averaged geocentric axial dipole direction at the site. This is likely to be satisfied in slowly cooled gabbros and slowly serpentinized peridotites. A key limitation in using paleomagnetism to constrain tectonic rotations is, in the case of sites drilled during Leg 209 and expeditions 304 and 305, the angular relationship between the direction of the pre-drilling magnetization and the azimuth of the rotation axis. This is particularly acute for those sites on the N-S striking MAR, at which likely rotation axes are very close in orientation to the geocentric axial dipole field direction. Even greater limitation occurs when only the inclination of the pre-drilling magnetization is available to be used. Garcés and Gee (2007) nevertheless interpret anomalously shallow magnetic inclinations of gabbro and peridotite samples exposed near the Fifteen–Twenty fracture zone (Leg 209) to infer that substantial rotations of between 50° and 80° of fault footwalls have occurred about horizontal, ridge-parallel axes, and that faults originally dipped steeply toward the spreading axis (Fig. 4.2).

Morris *et al.*, (subm. manuscript) made a paleomagnetic study of the 1.4 km long footwall section of gabbroic rocks from Hole U1309D. However, they reoriented gabbro drill core to a true geographic reference frame by correlating structures in individual core pieces with those identified from oriented electrical images of the borehole wall, following the methodology of MacLeod et al. (1992, 1994, 1995). This allowed them to reorient paleomagnetic data and more rigorously analyze possible tectonic rotations. Results indicate a 46°±6° counterclockwise rotation of the footwall around a MAR-parallel horizontal axis trending 011°±6°. This provides strong confirmation of the key prediction of flexural, rolling-hinge models for oceanic core complexes, whereby faults initiate at higher dips and rotate to their present day low angle geometries.

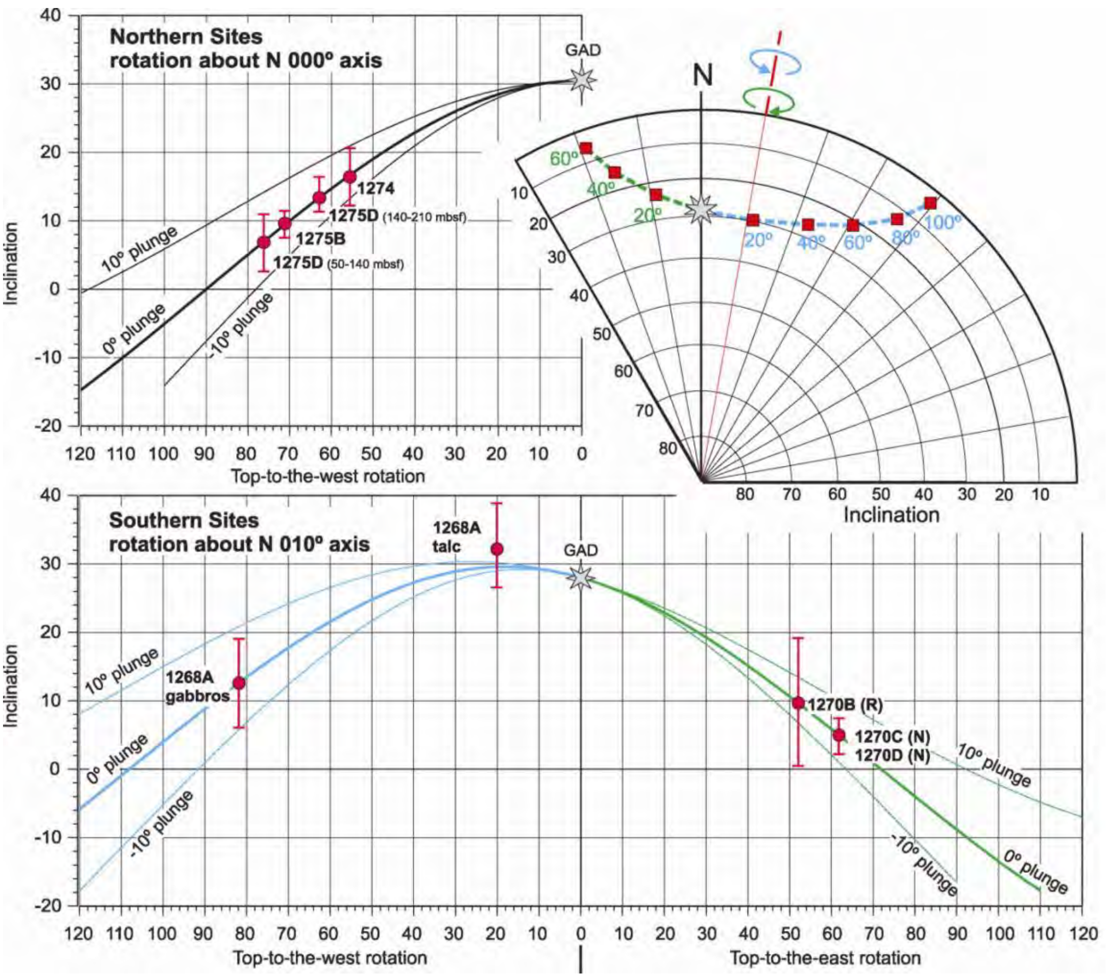


Figure 4.2 Model of effect of rotations on inclination data. Lines represent rotation of expected field vector (geocentric axial dipole, GAD) about given axis. Confidence bounds represent rotations about axes plunging ±10°. Model assumes that footwall uplift is accompanied by rotation of ridge flanks in sense top away from ridge (after Garcés and Gee, 2007).

The magnetic intensity pattern can be used for investigating the presence of multiple cooling units in sheet and massive flows lithology. An example appears in cores from Hole 1256D (Teagle *et al.*, 2006). Plots of the magnetic intensity against depth show a recurrent concave pattern (Fig. 4.3A), which shows reasonable agreement with the cryptocrystalline boundaries of igneous units and subunits. Higher intensities are related to upper and lower boundaries of 'cooling units', whereas lower intensity peaks occur within units. Although further shore-based analyses are required, these trends probably result from changes in the size and distribution of primary minerals (e.g. Petersen *et al.*, 1979), in particular titanomagnetite. About 70% of the igneous units and subunits drilled during Expedition 309 show repeated concave patterns (Fig. 4.3A), suggesting the presence of multiple cooling units (with the observed magnetic intensity pattern) within each lithologic unit. Their calculations suggest that the average thickness of these cooling units is ~1.0 ± 0.5 m (Fig. 4.3B).

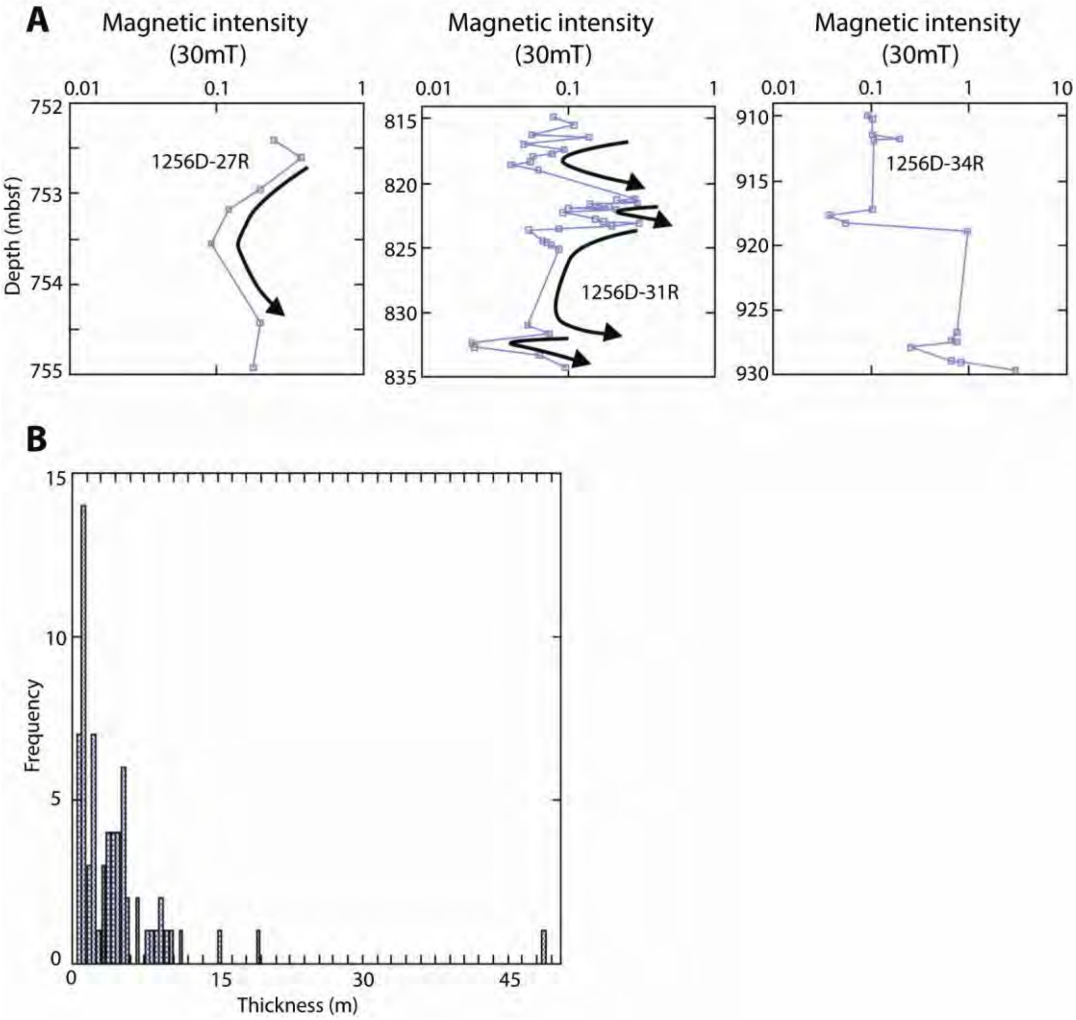


Figure 4.3 [A] Intensity variation in demagnetized archive-half samples that correlate with petrographic igneous units. From left to right: single behavior, multiple behavior, and irregular behavior. [B] Frequency of thickness (m) of concave shapes (after Teagle et al., 2006).

5. Thermal History, Alteration and the Deep Biosphere

5.1 Introduction

Fluid circulation is an important process transporting heat from young oceanic crust into the ocean. The associated seawater-rock reactions play a major role in buffering the isotopic and chemical compositions of seawater, and are intimately linked to the sub-seafloor biosphere. Prior to IODP, the upper crustal section recovered at ODP Hole 504B, representing oceanic crust generated at a fast-spread mid-ocean ridge system, was the only extensive reference point for understanding crustal accretion and associated hydrothermally driven alteration processes within ocean crust believed to compare to the ophiolite model (e.g. Alt, 1995; Alt *et al.*, 1996). Late ODP (Leg 206) and IODP drilling (Expeditions 309 & 312) at Site 1256 provided an important opportunity to establish a second reference frame for comparative studies in crustal structure, fluid circulation and fluid-rock alteration in a upper section of crust that formed at super-fast spreading rate. Significant differences can be identified.

In contrast to fast-spread ridges, slow- and ultra-slow-spread oceanic crust inherently show a highly heterogeneous structure with seabed exposure ranging from extrusives to lower crustal and mantle lithologies. This complex setting obviously is prone to show large lateral variation in deformation and hydrothermal alteration, and the presence of dominant detachment fault systems provide access for seawater to reach structurally deep lithologies including mantle peridotite. The associated serpentinization of mantle material has major consequences for long-term, global geochemical fluxes by acting as a sink or source for elements such H_2O, Ca, Mg, SO_4, Cl, B and by producing extremely reduced CH_4– and H_2–rich hydrothermal fluids (Früh-Green *et al.*, 2004). The discovery of the peridotite-hosted hydrothermal vent systems at the seafloor, such as the Lost City hydrothermal vents at the southern Atlantis Massif, has led to an intense interest in understanding the evolution of fluid-rock interaction in these systems, including the role of serpentinization in supporting hydrogen-based microbial communities.

5.2 Fast-Spreading Ridge Environments

Some of the major objectives with regard to understanding alteration processes at Site 1256 were to: (1) make direct observations of the transition from low temperature alteration to high temperature hydrothermal alteration in a continuous crustal section; (2) determine the variability of alteration processes in fast-spreading ridge environments and test current models of hydrothermal circulation and cooling; and (3) better understand how seawater circulation and alteration processes in magmatically robust environments differ from slow-spreading environments with variable magmatic input and strong variations in tectonic structure.

As reviewed below, objective (1) was achieved, objective (2) only in part (penetration into lower crust missing; probably an optimistic goal from the outset, given planned penetration). To achieve objective (3) obviously requires comparison with slow-spread crustal sections; drilling results at Site 1256, together with results from Hole 504B provides excellent reference material.

Alteration with depth and thermal gradients

The ~800-m-thick lava sequence at the top of Hole 1256D is less hydrothermally altered than other basement sites and shows no systematic change from oxidizing to reducing conditions of seawater-rock interaction with depth in the upper lavas. There is a stepwise increase in alteration temperatures downhole, from ~100°C in the lavas to ~250°C in the uppermost dikes. The distributions of secondary minerals are associated with steeply dipping vein networks, which indicate a structural control of alteration.

An important finding at Hole 1256D is that the lower ~60 m of the sheeted dikes (from 1348 to 1407 mbsf) are partially to completely recrystallized, showing a distinct granoblastic texture. This is interpreted to result from contact metamorphism by underlying gabbroic intrusions well in excess of the two gabbro bodies (52 m and 24 m respectively) recovered within the deepest part of the hole. Aside from the granoblastic contact metamorphic assemblages in the basal dikes, the hydrothermal mineral assemblages (Fig. 5.1) and inferred alteration temperatures of the lower dikes in Hole 1256D are generally similar to those in the lower dikes of Hole 504B (up to ~400°C). However, the much thinner dike section at Site 1256 than at Site 504 (~350m vs. ~1000 m) (Fig. 5.1) strongly indicates a much steeper hydrothermal temperature gradient at Site 1256 (~0.5°C m^{-1} vs. 0.16°C m^{-1} in Hole 504B) (Wilson *et al.*, 2006).

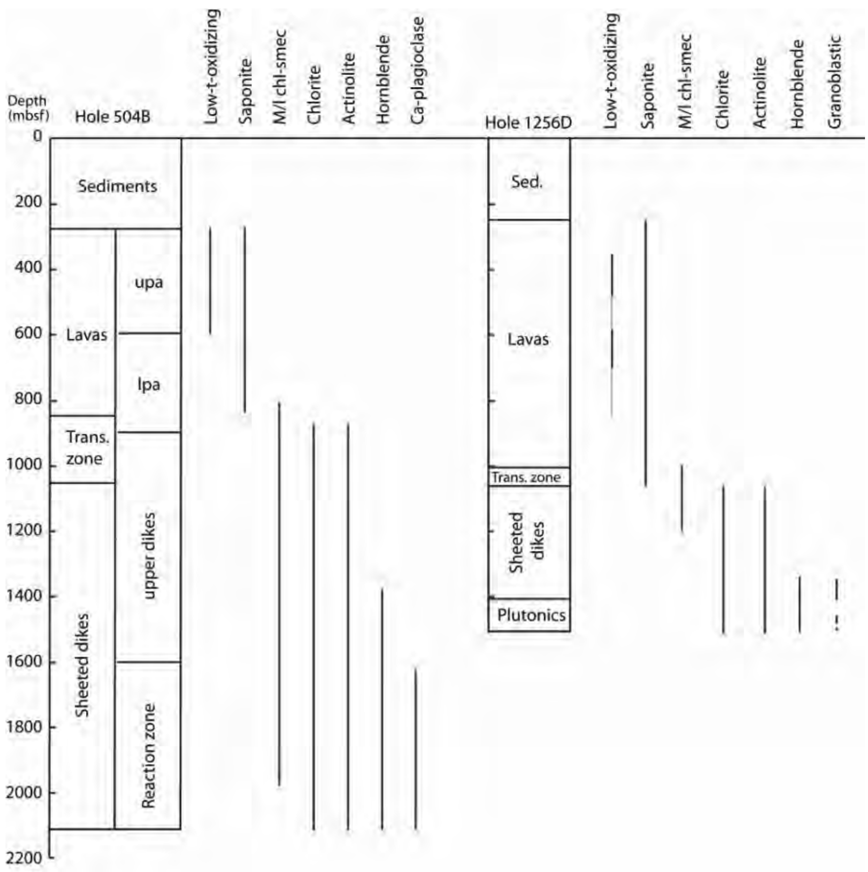


Figure 5.1 Comparison of lithostratigraphy and alteration types with depth in Holes 504B and 1256D. Low–t – low temperature, M l-1 chl–smec – mixed layer chlorite-smectite, upa – upper pillow alteration, lpa – lower pillow alteration (from Expedition 309 and 312 Scientists, 2006).

Although epidote is common within and below the transition zone in Hole 1256D, epidosites which are considered representative of the high temperature reaction zone in models of hydrothermal systems, were not encountered. Anhydrite in Hole 1256D is more abundant than in Hole 504B, but it is present in much lower quantities than predicted by models of hydrothermal circulation.

Constraints on models of hydrothermal circulation

The question of the degree to which the original melt lens below the spreading ridge crystallizes in situ, is cooled by vigorous hydrothermal circulation and advecting heat out of the system at sufficiently high rates remains unresolved, partly because deeper crustal penetration into the upper part of the lower crust was not obtained. However, the high thermal gradient inferred for the dike layer appears adequate to drive an advection system robust enough to transport latent heat of crystallization from the magma chamber and into the ocean. What is missing is a constraint of actual hydrothermal fluxes. Evidence for large fluid fluxes such as the presence of epidosites is lacking. Deepening the hole to extend the (paleo)thermal and alteration profile will be required in order to better address this point.

5.3 Slow-Spread Crust Environment

The expectation that large lateral heterogeneity and complexity in alteration (and protolith) may exist within slow-spread crust was fully confirmed by ODP Leg 209 and IODP Expeditions 304 & 305. This is perhaps best illustrated by the findings at the 1415.5 meter deep Site U1309 (Expedition 304 & 305). This targeted highly altered mantle lithology, expected to be strongly serpentinized in its upper part, and grading into less altered and more pristine mantle rocks in its deeper parts (around 800 mbsf). However, despite its proximity (see section 3.2 and Fig. 3.7) to the highly altered mantle rocks within its southern flank (including Lost City vent area), only an extremely limited amount of serpentinite derived from peridotites (<1%) was recovered at Site U1309. In addition, the gabbroic rocks that predominate in the hole were significantly less altered than the mantle rocks recovered at the Atlantis Massif.

Some of the fundamental questions to be addressed by drilling were:

1) How variable are alteration processes in slow-spreading environments, and what controls this variability?
2) What is the depth of seawater penetration and what is the role of faults in transporting mass and heat?
3) What are the consequences of serpentinization for geophysical properties and the nature of the Moho (i.e., the Moho as an alteration front), and for fluid fluxes and mass transfer in peridotite-dominated domains of OCCs?
4) What is the nature and depth of the deep biosphere? How does it vary in gabbroic- versus peridotite-dominated domains?

Important information was obtained for questions 1, 2 and 4, while 3 remained in part unaddressed. However, although the amount of serpentinized peridotites recovered was minimal, valuable information was gained as to the depth of seawater penetration into the core of the massif, and comparison studies of rocks acquired from the southern wall provide constraints on the extent of present-day hydrothermal circulation into the massif.

Heterogeneous lithologies and conditions of alteration

Numerous investigations at the Atlantis Massif have revealed a complex lateral and vertical heterogeneity in composition, alteration, and deformation of this OCC. Early high-temperature metamorphism under granulite to amphibolite conditions is widespread at the southern wall, but are less prevalent in the gabbroic rocks drilled at the central dome. Deformation and alteration is dominated by greenschist-facies conditions (<500°C) and is generally restricted to the upper 800 m of Hole U1309D or to fault zones (e.g. 695–785 mbsf). However, some amphibolite-facies metamorphism may have been coincident with the latest stages of magmatism. In particular, late leucocratic dike injection and crystallization and late crystallization in the oxide gabbros appear to be continuous across the transition between fluid-rich late magmatism and amphibolite and, ultimately, greenschist-facies hydrothermal metamorphism.

The degree of alteration in the gabbroic rocks at Hole U1309D decreases downhole (Expedition Scientific Party, 2005a, b; Blackman *et al.*, 2006) (Fig. 5.2) and, in general, is greater in the olivine-rich rocks and correlates with the presence of faults. In the upper 350 m, alteration is nearly pervasive and does not generally reflect focused fluid flow. With increasing depth, greenschist-facies hydration is almost always related to veins, igneous contacts, and other fluid conduits. Zeolites only occur below 750 mbsf, where ambient conditions are >80°C, suggesting that the gabbros cooled rapidly from temperatures of about 300°C. Cooling may be related to seawater circulation along faults, and highlight differences in pathways of seawater penetration and hydrothermal circulation between fast- and slow-spreading ridge environments.

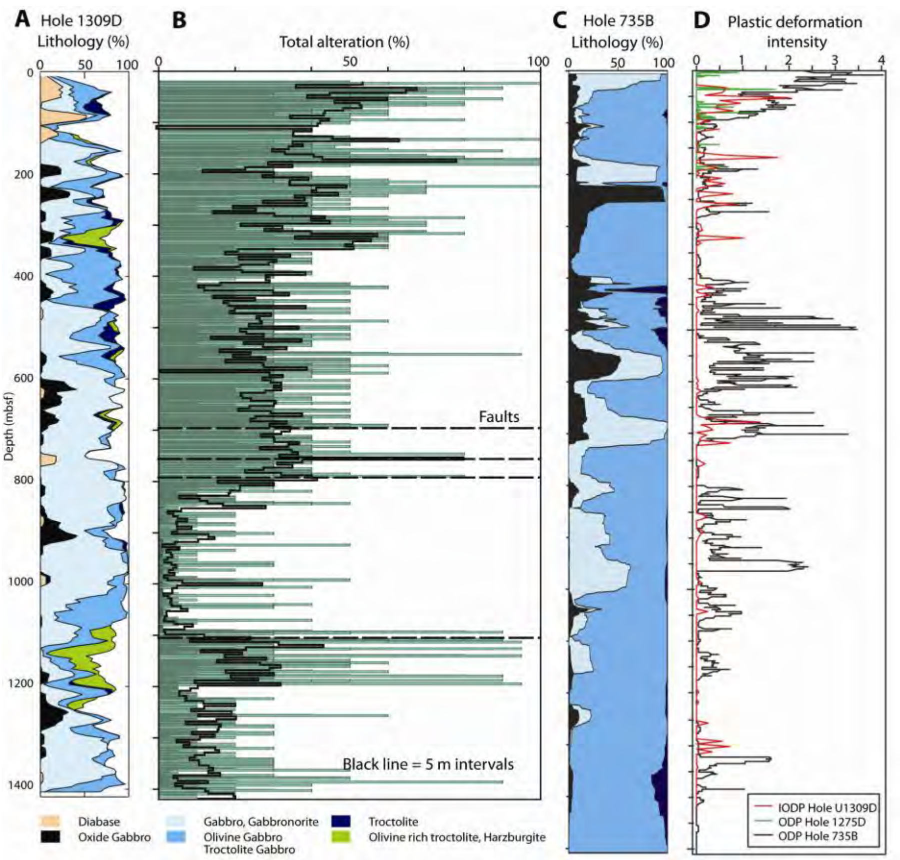


Figure 5.2
Summary of lithology and deformation in boreholes penetrating oceanic core complex: [A] core U1309D lithology (20 m running average),
[B] downhole alteration logged during visual description of the core (after Blackman et al., 2006),
[C] core 735B lithology (20 m running average) (after Dick et al., 2000),
[D] crystal-plastic deformation intensities for all cores. Deformation intensity scale:
0 – undeformed,
1 – weakly foliated,
2 – strongly foliated,
3 – porphyroclastic,
4 – mylonitic.
(from Ildefonse et al., 2007).

Deformation and fault zones

Extensive granulite-facies and amphibolite-facies deformation in Hole U1309D is limited, and high-strain ductile shear zones are rare, with <3% of the core showing brittle or crystal-plastic fabric (Blackman *et al.*, 2006; Ildefonse *et al.*, 2007). These results contrast greatly with the thickness and intensity of deformation and metamorphism recorded in the gabbroic section of Hole 735B (Southwest Indian Ridge), which is distinctly more deformed (Fig. 5.2). The drillcore from Hole 735B record extensive, high-temperature crystal-plastic plastic deformation and contain numerous mylonitic shear zones as thick as 20 m (Dick *et al.*, 2000). In addition, an association of magmatic and crystal-plastic foliations with oxide abundance, and the presence of numerous intrusions of late stage, oxide-rich melts focused along small shear zones distinguish the Hole 735B section from the gabbros of Sites U1309 and 1275 (15°45' N) and from gabbroic sections in most well documented ophiolites.

No clear zone of detachment faulting was recovered in the Site U1309 drill cores; however, the existence of a fault at the top of the dome is supported by fragments of brecciated talc-tremolite fault schist and fractured metadiabase recovered in Hole U1309B and in the series of shallow cores drilled. Since the drilling strategy used during the expeditions prohibited the recovery of possible detachment sequences in the upper ~20 m of the holes, the paucity of unequivocal fault rocks suggests that the fault zone(s) comprising the detachment system must be highly localized to within tens of meters of the present-day seafloor.

Results of drilling also contrast greatly with investigations of the AM south wall, which documented an ~50–100 m thick zone of strongly foliated serpentinites and talc-amphibole schists representing the mylonitic detachment shear zone along the crest of the massif (Boschi *et al.*, 2006a; Karson *et al.*, 2006). Extensive talc-amphibole-chlorite metasomatism characterizes the strongly foliated zone of detachment faulting. Studies of Boschi *et al.* (2006a) demonstrated the complex interplay of fluids, mass transfer, and metamorphism in strain localization associated with the evolution of the detachment shear zone and development of this OCC. Comparisons with other studies of OCC along the Mid-Atlantic Ridge indicate that talc-bearing metasomatic fault rocks are key elements of detachment shears zones in lithospheric sections comprised of peridotite intruded by gabbro (e.g. MacLeod et al., 2002; Escartin *et al.*, 2003; Boschi *et al.*, 2006b; Dick *et al.*, 2008). Major and trace elements indicate a complex mutual interaction between gabbroic and ultramafic rocks during metasomatism, which together with microstructures, suggest localized circulation of oxidizing, Si-Al-Ca-rich fluids and mass transfer in high strain deformation zones.

Fluid-fluxes

Strontium and Nd isotope data (Delacour *et al.*, 2008a) of the central dome indicate that seawater alteration is concentrated at shallow crustal levels and is related to serpentinization of the mantle peridotites and alteration of olivine-rich gabbros and leuco-gabbros. Below 800mbsf, the gabbroic rocks and olivine-rich troctolites preserve mantle isotopic compositions attesting to relatively limited seawater interaction. However, minor variations away from mantle compositions likely reflect minor circulation of fluids channeled in fault zones (Fig. 5.3). In contrast, Sr, Nd and S isotope analyses of the basement rocks of the southern wall reveal changes towards seawater values reflecting high fluid fluxes related to the Lost City hydrothermal system (Delacour *et al.*, 2008a, b, c; Fig. 5.4). An important effect of higher fluxes is a change to more oxidizing conditions and the oxidation and loss of mantle sulfide. In addition, geochemical studies of Delacour *et al.* (2008b, c) and Boschi *et al.* (2008) indicate that the serpentinites at the Atlantis Massif are a significant sink for boron, sulfate and dissolved organic carbon from seawater.

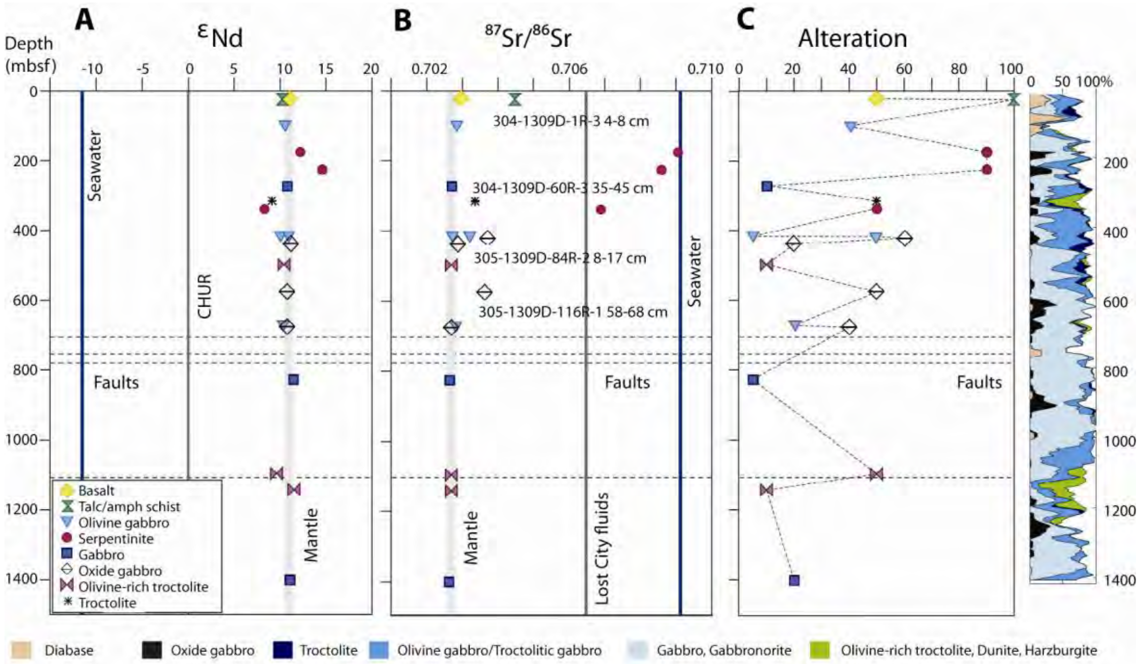


Figure 5.3 Comparison of εNd values, 87Sr/86Sr ratios, and alteration with depth and lithostratigraphy at IODP Hole U1309D at the central dome of the Atlantis Massif (from Delacour et al., 2008a). Depths of fault gouges identified by the IODP Shipboard Scientific Party are shown as horizontal dashed lines (695, 756, 785 and 1107 mbsf; Expedition Scientific Party, 2005a; 2005b; Blackman et al., 2006). Sr isotope composition of the Lost City end-member fluid (from Ludwig et al., 2006).

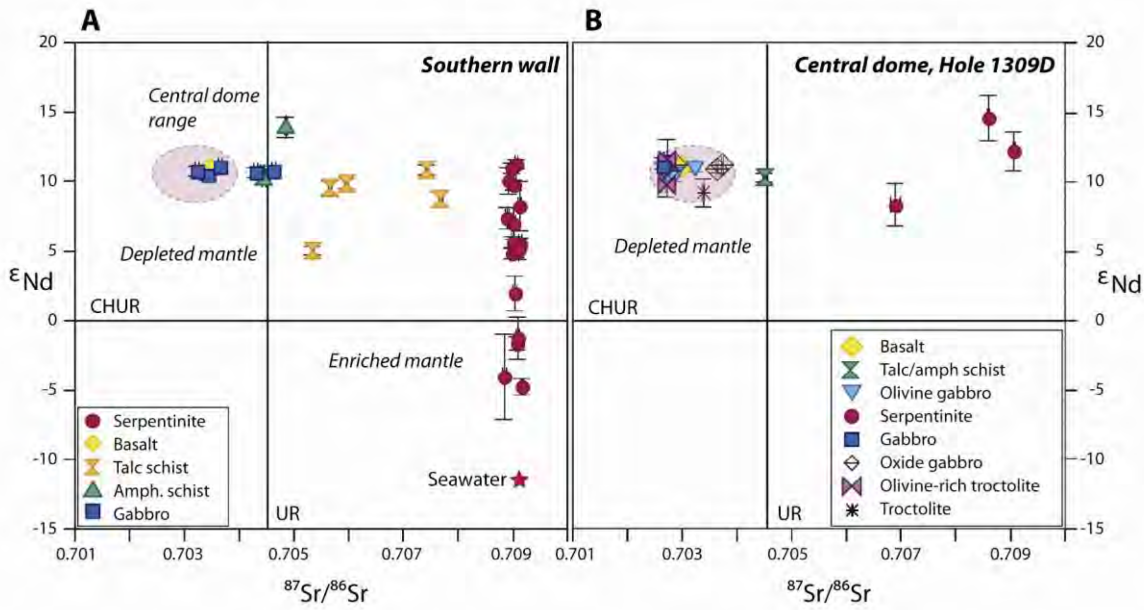


Figure 5.4 Variation in εNd versus 87Sr/86Sr for samples [A] from the southern wall of the Atlantis Massif and [B] drilled at IODP Hole U1309D of the central dome. The internal error-bars (2s), the εNd composition of the CHUR (CHondritic Uniform Reservoir of 0.512638), and the Sr isotope composition of the UR (Uniform Reservoir of 0.7045) are shown for reference (from Delacour et al., 2008a).

Comparison with other OCCs

Drilling at Atlantis Massif revealed similar relationships to those encountered at Site 1275 at the15°45' N OCC, in that serpentinized peridotites are exposed on the seafloor but are nearly absent in the deep boreholes. Both have fault rocks at the seafloor and late intrusion of basaltic dikes. In both cases the gabbro bodies have undergone little high-temperature deformation. Results from ODP Leg 209 indicate significant variations in mantle compositions, serpentinization reactions and conditions of alteration. Alteration of the Leg 209 peridotites occurred over a range of temperatures from ~350°C to <250°C and is attributed to three distinct processes: rock-dominated serpentinization with formation of brucite in olivine-rich lithologies, fluid-dominated serpentinization with formation of magnetite and no brucite, and fluid-dominated talc alteration with addition of SiO_2 as well as H_2O and oxygen (Bach *et al.*, 2004). The latter two processes also exhibit detectable trace element metasomatism that is distinct in its character from the igneous impregnations (Paulick *et al.*, 2006). In-situ analysis by secondary ion mass spectrometry by Vils *et al.* (2008) reveals that the B, Li and Be contents of mantle minerals remain unchanged during serpentinization. Serpentine minerals are enriched in B and depleted in Li compared to the primary phases, and show considerable variation within and between samples.

5.4 Microbiology and Constraints on a Deep Biosphere

Microbiological studies of gabbroic and mantle sequences recovered by drilling are still in their infancy, and little information is available with regard to understanding the extent of the deep biosphere in the oceanic crust. Although a microbiologist was onboard both Expeditions 304 and 305, results and a submitted manuscript are only available from Expedition 305 (Mason *et al.*, 2008; Mason *et al.*, unpublished). Rocks were collected for molecular analyses from depths of 400 to 1400 mbsf and aerobic bacteria were cultured in variable rock types (gabbro and ol-bearing gabbro), with variable (10–50%) alteration, to depths of >1300 mbsf (T >75°C). Mason *et al.* (unpubl.) had no success culturing bacteria from the troctolites, and no archaea were found in any of the samples. The microorganisms cultured from the central dome are most similar to organisms known to degrade hydrocarbons, and are distinct from those cultured from hydrothermal carbonates from the Lost City hydrothermal field (Brazelton *et al.*, 2006). At Lost City, variable mixing with seawater creates strong temperature and chemical gradients that provide micro-niches for distinct microbial communities within the carbonate towers. The actively venting structures, characterized by the highest temperatures and most H_2– and CH_4–rich fluids are dominated by anaerobic Archaea Methanosarcinales and H_2 and S–oxidizing bacteria. The results of Brazelton *et al.* (2006) show that the microbial communities become more diverse with progressive mixing with seawater and are dominated by aerobic and anaerobic methanotrophic and S–oxidizing bacteria in the extinct, older structures. These results highlight the fact that a deep hydrogen-based biosphere is likely to be extensive in serpentinizing environments and infers that microbial communities may differ, and be more dependent on brittle faults and fractures, in thick gabbroic domains in a heterogeneous lithosphere.

6. Drilling the Oceanic Crust and Studies in Ophiolites: Cross-Fertilization

6.1 Introduction

The structure and the composition of the lower oceanic crust (also referred to as 'oceanic layer 3' or as 'gabbroic crust') are largely inferred from a comparison between seismological data and geological observations in ophiolites (e.g. Christensen and Smewing, 1981). Detailed studies of ophiolites have been even more critical to constrain mantle processes related to crustal accretion including mantle flow pattern, melt migration, etc. (e.g. Nicolas et al, 1988; Nicolas, 1989; Ceuleneer and Rabinowicz, 1992; Ceuleneer *et al.*, 1996; Kelemen *et al.*, 1997). The resultant ophiolite based model for oceanic crust and lithosphere is often referred to as the Penrose Ophiolite model (Anonymous, 1972). However, while ophiolites safely can be regarded remnants of some sort of oceanic spreading centers, subsequently obducted on to the continent, their original tectonic setting is poorly constrained. Are they truly equivalents of crust that formed at mid-ocean ridges, and if so, at what rate of spreading? Or do they represent special back-arc crust possessing unique features, which in turn have been overprinted by subsequent tectonic displacement during closure of the marginal basin in which they formed? Ocean drilling of complete crustal sections in well constrained settings (fast and slow spread, proximity to transform faults etc.) can provide critical help to understand the importance of the detailed observations within ophiolites, which in turn make these a much better platform for understanding the formation of oceanic crust. Below are some examples of important opportunities for cross-fertilization between ocean drilling and shore-based ophiolite studies. An important conclusion is that ocean drilling not only addresses questions of confirming the ophiolite model, but also questions that can lead to (1) a better understanding of the many features within ophiolites, and, in turn, their bearing on ocean crust formation; and (2) help understand the dissimilarities between ocean crust and ophiolites.

6.2 Structure of the Gabbroic Crust and Magma Chambers at Fast-Spread Ridges

It has taken nearly 30 years to make a first important step towards validating or invalidating the classic "Penrose ophiolite model" by confirming, in one single location, the presence of all three major crustal components depicted by the model: Extrusive uppermost crust, sheeted dike-complex within the lower upper crust and gabbroic lower crust representing the top of the lower crust.

IODP Expedition 312 crowned three expeditions by recovering in Hole 1256 gabbro from 1407 mbsf below intact, Penrose-type oceanic upper crust (see section 2.2). Drilling operations, however, stopped at what likely is the transition between the sheeted dike complex and the 'roof' of a former magma chamber from which an approximately 4 km thick lower gabbroic crust might have been fed. Moderate deepening at Site 1256 should allow us to recover layered gabbros like those of Figure 6.1, typically found in ophiolites, but not in Hole 1256. In fact, layered gabbros, typical in ophiolites, have hardly been recovered in any in situ gabbroic section from the oceanic crust.

Figure 6.1 Typical layered gabbros from Oman, showing well developed, although discontinuous, modal graded bedding. Such structures have not been documented yet in present day oceans. A reasonable hypothesis is that they form at the center of fast-spreading mid-oceanic ridge segments. This hypothesis can be tested by deepening Hole 1256 (Photographed by Georges Ceuleneer).

Layered gabbros show well developed, modal graded bedding, which together with geochemical data (Fig. 6.2), is diagnostic of fractional crystallization and mixing in magma chambers. As shown in Figure 6.1, each layer is not continuous laterally, pointing, to dynamic processes involving viscous flow in a crystal mush, possibly melt convection (e.g. Nicolas and Ildefonse, 1996).

Figure 6.2 illustrates the kind of geochemical evolution observed in the deep crust exposed in Oman. Most geochemical parameters diagnostic of fractional crystallization in response to cooling do not evolve up section in the layered and foliated gabbros (LG and FG), pointing to frequent replenishment of the magma chamber with high temperature, primitive melt batches. In contrasting to this situation, a huge scatter in the values of the same parameters is observed in a shallow horizon of "vari-textured gabbros" (VG).

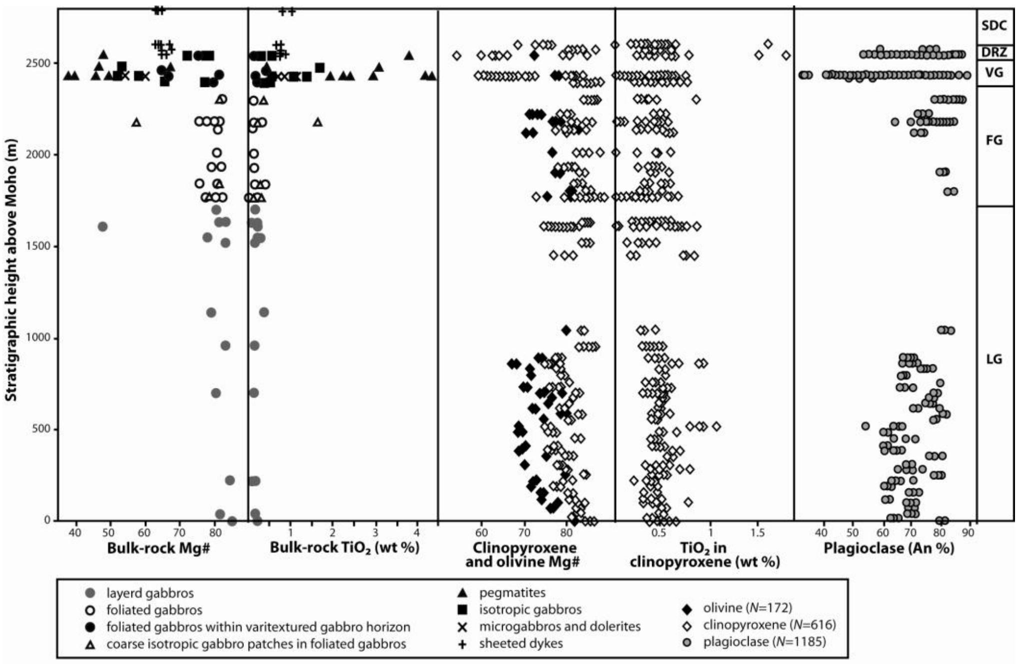


Figure 6.2 Geochemical evolution of the lower crustal gabbros in the Oman ophiolite (from MacLeod and Yaouancq, 2000).

This horizon is interpreted as resulting from accumulation and *in situ* crystallization of variously evolved magmas in a melt lens below the sheeted dyke complex (SDC). The Hole 1256D stopped precisely at the transition between the sheeted dyke complex and isotropic gabbros that is supposed to correspond to the upper part of the log in Figure 6.2. Accordingly, continuation of this hole would allow us to test if a compositional trend similar to the one observed in Oman characterizes the gabbroic crust formed along present-day fast spreading ridges. Such data would be particularly useful in addressing the existence of open magma chambers at fast-spread mid-ocean ridges.

While the limited penetration of Hole 1256 prevent us from knowing if such layered gabbros, a common feature within ophiolites, are present at fast-spread mid-ocean ridges, prevailing data indicates that they are not common features in slow-spread crust (Fig. 6.3) (e.g. Ildefonse *et al*., 2006). Constraining the occurrence of modally layered gabbros within known oceanic crustal environments would be a major achievement with significant consequences for our understanding and modeling of magma chamber processes at mid-ocean ridges (Fig. 6.3) (e.g. Chevenez *et al*., 1998). Hole 1256 offers the opportunity to make an important step in this direction.

6.3 Deformation Structures: Related to Spreading and not Thrusting?

Large bodies of gabbro were successfully cored in slow spreading environments during the recent IODP Expeditions 304 & 305 at Site U1309 (Atlantis Massif Oceanic Core Complex). Observations from this site together with previous achievements of ODP (e.g. Hole 735B), suggest that deformation features commonly observed in ophiolites may actually have formed during the process of plate divergence, rather than during obduction as commonly interpreted.

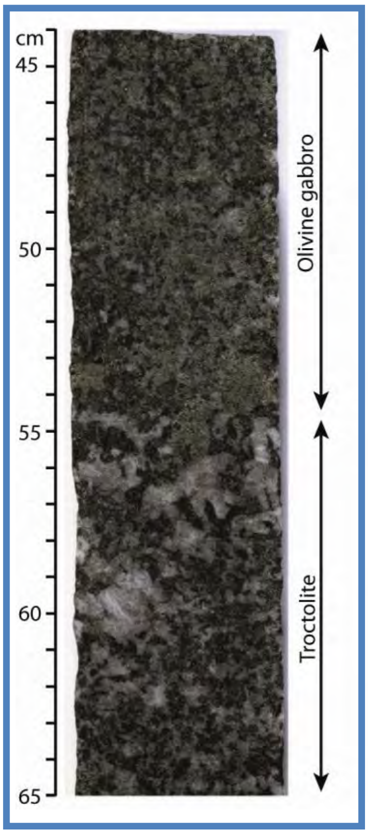


Figure 6.3 Layered gabbros are not a common feature in slow spreading environments. When observed (here at Site U1309, Atlantis core complex) its aspect contrasts significantly with the one commonly documented in ophiolites: modal graded bedding is less developed and marked textural variations are the rule. Lithological contacts are more abrupt, the lithological diversity is more developed and geochemical variations are more erratic (Ildefonse et al., 2006; Suhr et al., 2008). It calls for contrasted crustal building processes (melt injection, crystallization) at slow spreading ridges and in ophiolites, at least in those (or parts of those) presenting well developed sections of layered gabbros, which also the ones used to constrain magma chambers models (from Blackman et al., 2006).

The notion that major normal faults may root in crystallizing magma bodies is one of the major achievements of recent drilling at oceanic core complexes in slow-spreading mid-oceanic ridge settings. Syn-magmatic block rotation observed in ophiolites could, accordingly, develop in such contexts; at least this is a hypothesis that is worth testing. In turn, ophiolites offer a unique opportunity to study the details of the interaction between faulting and the crystallization of a magma chamber, and give a precise conceptual frame to interpret changes in the dip of magmatic layering downhole drilled sections of oceanic gabbros.

Ocean drilling has largely contributed to illustrate that ductile shear zones developing in the gabbroic crust are preferentially focused in the most evolved cumulates (i.e. those crystallizing from the lower temperature melts) (e.g. Cannat *et al.*, 1997). Here also, such a relationship between petrologic evolution and deformation is commonly observed in ophiolites (e.g. Python and Ceuleneer, 2003). Figure 6.4 shows a sheared gabbronorite in the Oman ophiolite. The classical interpretation of such features in ophiolites is that gabbronorites were emplaced and deformed during thrusting and not during accretion, a conclusion that needs to be reconsidered in light of recent drilling results.

Figure 6.4 High temperature mylonitic deformation affecting gabbronorite, Oman ophiolite (Photographed by Marie Python).

6.4 Melt Migration Mechanisms

The uppermost part of the mantle was sampled during ODP Leg 209. This offered a unique opportunity to address melt migration models previously based almost entirely on studies of mantle sections within ophiolites. The latter have shown evidence for interactions between the residual mantle and the melts migrating to the crust (e.g. Quick, 1981; Ceuleneer *et al.*, 1996; Kelemen *et al.*, 1997)(Fig. 6.5). Melts produced at depth and migrating to the surface are under-saturated in silica relative to pyroxene bearing assemblages. Pyroxene dissolution then favors the development of high porosity channels in the shallow mantle (Kelemen *et al.*, 1997). Does such porous flow channels provide an efficient melt migration path from the zone of melt production to crustal magma chambers? The recovery of dunitic intervals associated with mantle harzburgite during Leg 209 (Takazawa *et al.*, 2007) suggests that this is a possibility (Fig. 6.6). However, Leg 209 also recovered widespread evidence for more diffuse melt impregnation along grain boundaries, and no constraints exists on the relative role (flux) of melt by these two different end members in term of magma migration. Also, surprisingly, results of Leg 209 and 304 & 305 jointly suggests that in fact, while such 'crustal' melts formed and migrated upwards, they only partly, if at all, left the mantle and formed a 'crust' but remained in the mantle host, in part as very voluminous bodies. Melt retention within the mantle of the scale indicated by the findings of Leg 209 (Kelemen *et al.*, 2007), and Expeditions 304 & 305 is surprising, if not paradigm changing, and might instigate new research within ophiolites.

Figure 6.5 Porous flow channel with evidence for dissolution of mantle pyroxene and formation of dunitic walls in the supra-subduction zone Trinity ophiolite (Photographed by Georges Ceuleneer).

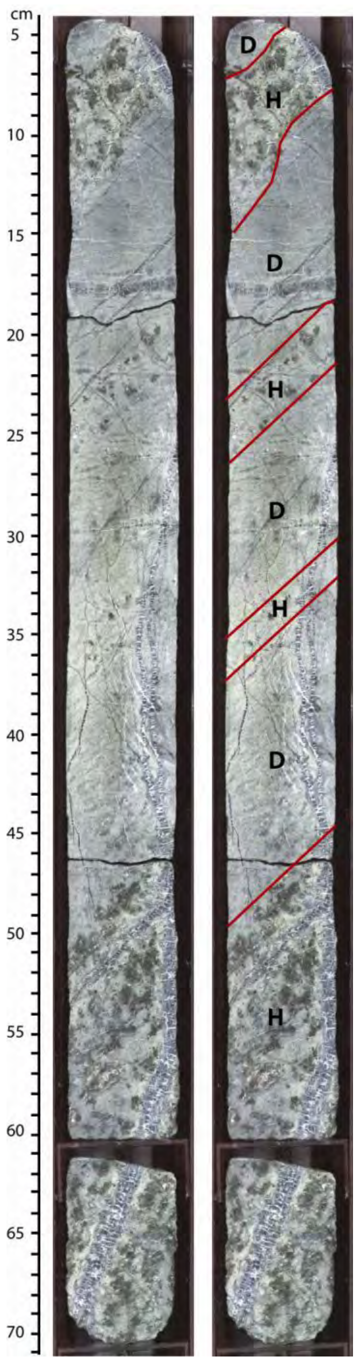


Figure 6.6 Dunitic intervals drilled along the Mid-Atlantic Ridge, 15°N area, ODP-Leg 209 (modified after Kelemen, Kikawa, Miller, et al., 2004).

6.5 Andesitic Affinity Magmas at Mid-Ocean Ridges?

Many ophiolites shows 'arc-like' petrological and geochemical affinity (e.g. Pearce *et al*., 1980, 1984; Python and Ceuleneer, 2003; Arai *et al*., 2006; Python *et al*., 2007) In addition, frequent intrusions and dykes cross-cutting both the mantle section and the crustal section of these ophiolites crystallized from melts richer in silica, more andesitic, than MORB. As a consequence, pyroxenes preceded plagioclase in the crystallization sequence and rocks like wehrlites, websterites, opx-rich gabbronorites (Fig. 6.7) formed. Moreover, their parent melts were derived from a mantle source depleted in most incompatible trace elements, including the high field strength elements (HFSE).

These observations from ophiolites support a supra-subduction zone setting of these ophiolites. However, in the case of Oman, there is no geologic evidence for the development of a volcanic arc at the time of its formation (see Python and Ceuleneer, 2003). This has led to the concept of ophiolite generation as a short-lived event that immediately follows intra-oceanic subduction initiation (e.g. Stern and Bloomer, 1992). Alternatively, since melting of refractory peridotites in conditions of water saturation can occur at relatively low temperature (around about 1000°C; melts produced will be enriched in silica.), some petrogenetic processes acting at ocean spreading centers may mimic the hydrated melting of the residual mantle that leads to the typical Arc signature.

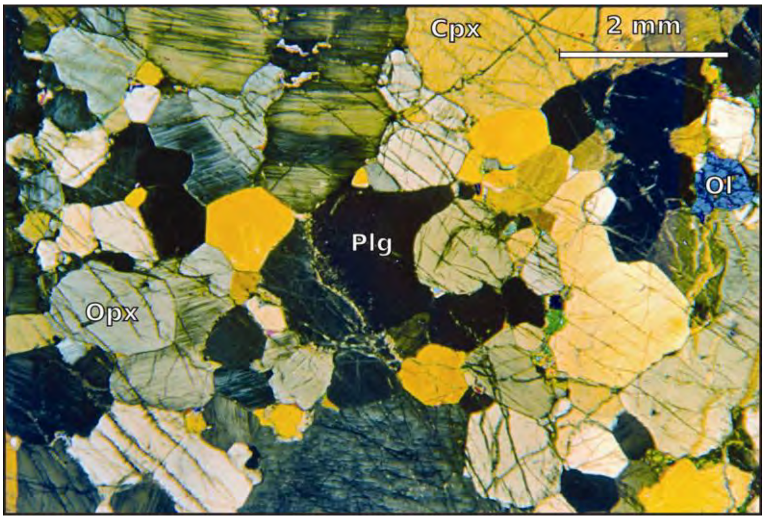


Figure 6.7 Opx-rich gabbronorite commonly found as intrusions in the Oman ophiolite and less commonly along present-day ridges. The euhedral shape of opx, and the interstitial habit of plagioclase, indicate that opx preceded plagioclase in the crystallization sequence and points do an andesitic parent-melt (Photographed by Marie Python).

It has been proposed that such a process might result from episodic rise of asthenospheric diapirs below mid-ocean ridges (Benoit *et al.*, 1999). In fact, rocks sharing their opx-rich modal composition and depleted signature with andesitic lithologies found in ophiolites have been recovered at Site 334 (Mid-Atlantic Ridge). Their geochemical composition mimics the one of boninites and andesites found along present-day subduction zones (Aumento *et al.*, 1977; Ross and Elthon, 1993). Isotopic data confirm (Fig. 6.8) that seawater was involved in their genesis (Nonnotte *et al.*, 2005).

In conclusion, distinct structural and petrologic features of ophiolites commonly attributed to late stage thrusting and arc processes rather than primary crustal formation by spreading have been found by ocean drilling to also occur within slow-spread ocean crust. As a consequence, we should reconsider the ophiolitic record in the light of these results, and not discard these features as being non-representative of spreading ridge processes.

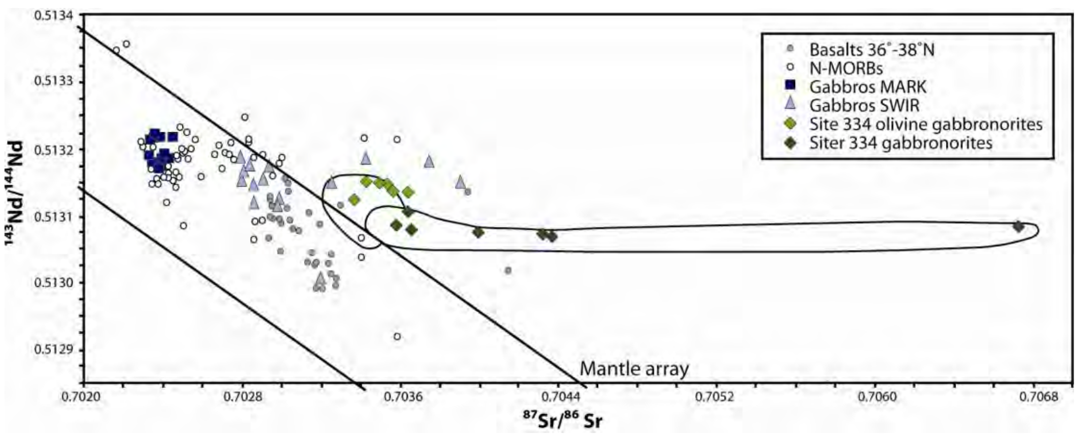


Figure 6.8 Isotopic signatures of cpx from Site 334 gabbronorites. These cpx have been intensely leached to remove the effects of post-crystallization alteration. High 87Sr/86Sr ratio associated to 'normal' 143Nd/144Nd show that their parent melt was issued from hydrated melting of mantle rocks (from Nonnotte et al., 2005).

7. Ocean Crust Drilling: Technology Issues

7.1 Introduction

The review panel considered what are the most significant technological impediments to achieving IODP ISP solid earth scientific objectives. The challenges we have historically faced (and have yet to completely overcome) include initiating and deepening holes in oceanic basement, drilling deep holes in oceanic basement, core orientation in basement lithologies, and drilling-induced magnetic overprint.

Successes in oceanic crust coring in IODP

1) Deep penetration (>1400 mbsf) at two different crustal sections
2) Initiating a deep well in a sloping environment with thin sediment cover
3) Drilling a continuous section through oceanic seismic layer 1 and 2A and into the lowermost part of layer 2B

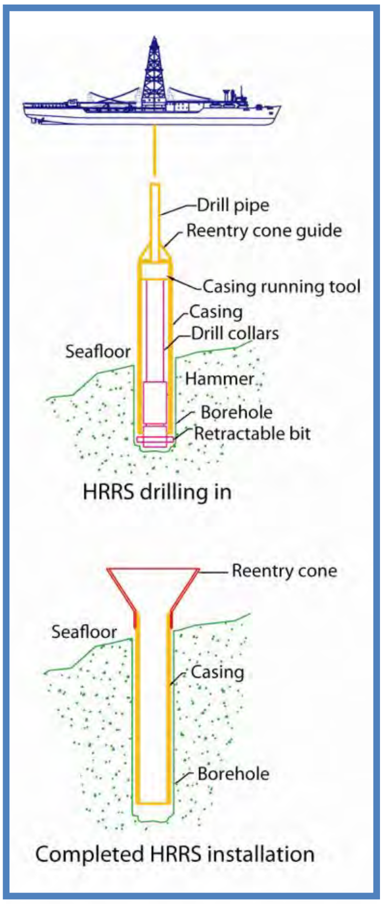
Opportunities for future progress

1) Hard rock core orientation
2) Reducing drilling induced magnetic overprint
3) Diamond coring (improving recovery quality and quantity)
4) Deep crustal penetration

7.2 Coring Oceanic Basement

Historically, scientists have seen limited success in coring exposures of oceanic basement, particularly young volcanic upper crust. Dozens of attempts at coring young oceanic crust (the most recent during ODP Leg 209 and IODP Expedition 304) were typical examples of a few meters penetration and exceedingly poor recovery before holes were abandoned. While no direct evidence exists, the opinion of drillers and scientists is that the rubbly topography associated with morphologically youthful basalt entraps the bit, increasing torque and either halting penetration or fracturing the formation to the point recovery is effectively nonexistent. However, drilling in older basalts (e.g., ODP Legs 104 and 152) have been quite successful, and land drilling by other programs within young basalts has been phenomenally successful in Hawaii and in Iceland, strongly suggesting that it is the drilling/coring process ODP/IODP employs within young basalts that is the problem. Following the success of sampling deep oceanic crust on ODP Leg 118, ODP/IODP have seen noticeable improvement in ability to core and recover oceanic gabbroic rocks, aided, in case of bare rock drilling, by a stable seafloor reentry template.

The first hurdle to overcome in coring young oceanic crust is initiation of the borehole. The portable seafloor reentry templates (hard rock guide bases) that commonly stymied basement sampling expeditions during ODP have effectively been retired in favor of the hydraulic hammer-in casing system developed during ODP Legs 179 and 193 and IODP Expedition 304 & 305 (Fig. 7.1). Slope dependence, thin



sediment cover, and theoretically rubbly terrain are no longer impediments to coring basement exposures. Whereas young crust borehole initiation was unsuccessfully attempted during IODP Expedition 304 with the hammer drill, the deployment was not an optimum tool design, and we have yet to attempt to deploy the hard rock reentry system (HRRS) with optimized components in a morphologically youthful oceanic basaltic crust environment. Downhole well control (preventing borehole collapse below the reentry template conduit) will require additional engineering and modification to the HRRS. A dual hammer system, entailing a lower hammer for initiating a hole and an upper hammer to drive casing into the formation (as opposed to gravity feed) might isolate a sufficient interval of the unstable top of the formation to allow deeper penetration. The hard rock reentry system, however, is still developmental. The hydraulic hammers are considered mature developments by the vendor, however, coupling the hammers to the reentry templates is still a significant engineering challenge.

Figure 7.1 Schematic of the Hard Rock Reentry System HRRS (from Graber et al., 2002).

During ODP Leg 193, the advanced diamond core barrel (ADCB) proved to be the coring tool of choice in intensely fractured, morphologically youthful lava flows (Fig. 7.2). Whole-round intervals with insufficient integrity to hold together after removal from the core liner were recovered intact using diamond coring, which is the coring apparatus of choice in many on land applications (e.g., Iceland). While promising, the ADCB is still in its developmental infancy. Based on thin kerf diamond technology, drilling with this or any diamond coring system requires minimal Weight on Bit (WOB) variation and thus is dependent on adequate heave compensation and/or platform stability. In addition, in its current design phase, the reduced strength of the ADCB bottom hole assembly precludes initiating a borehole with this system. Further engineering developments are required to bring this system to maturity for potential applications in hydrothermal systems, zero-age crust, and faulted terrains. The review panel also noted that perhaps the larger and inherently more stable *D/V CHIKYU* drilling platform might support diamond-coring tools better than the *D/V JOIDES Resolution* drilling platform. Heave versus sea-state statistics for the two platforms should indicate possible opportunities in this regard.

7.3 Core Orientation

A longstanding objective of scientific drilling in oceanic crust has been to apply structural reorientation to recovered cores. In high-recovery, sediment sampling projects, core orientation is primarily used to normalize the relative paleomagnetic pole directions to the current absolute pole direction. Measurements of relative orientation of stratigraphic and deformational structures can then be converted to absolute orientation.

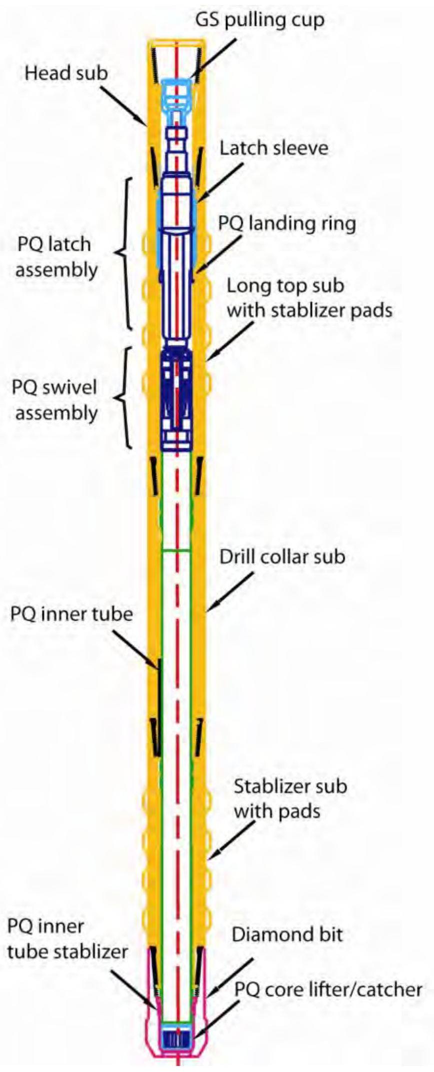


Figure 7.2 The Advanced Diamond Core Barrel (ADCB) coring system may be used to attempt to recover continuous core samples from firm to well lithified sedimentary or igneous formations (from Graber et al., 2002).

Although logging data can provide an indirect core orientation based on correlation of corresponding features measured in cores and borehole walls, incomplete core recovery most commonly prevents unique correlation between specific intervals of rock and the logging data.

Orientation of multiple pieces of rock or semi-lithified core samples recovered in one core barrel, such as those collected using the extended core barrel (XCB) or rotary core barrel (RCB), poses unique challenges. A sophisticated combination of measurement techniques must be employed to detect when core is recovered and when it is being ground away (depth component) as well as the azimuth at which the core piece being cut originated (before it is broken out of the formation). Designs for hard rock core orientation tools were tested during ODP but required multiple systems working in coordination to function. The various components of a hard rock core orientation system (scribe, sonar target, sonic monitor, transducer, and rig instrumentation) have been designed or will be available on the refit *D/V JOIDES Resolution*. Some components have not been constructed owing to redirected engineering efforts and routine hard rock core orientation is not possible without further engineering development.

7.4 Drilling-Induced Magnetic Overprint

The history and challenges of drilling-induced magnetic overprint (DIMO) causes and attempts at solutions have been fairly well documented in manuscripts describing magnetic experiments from ODP Legs 146, 174B, 182, 189, and 202. DIMO has been interpreted to result from recovering cores in magnetized drill string components. DIMO has been attributed to routine jarring, vibrations, and rotational stresses imparted during drilling operations. Options to mitigate DIMO range from continual degaussing of the drill string to replacing some or all drill string components with nonmagnetic materials.

Recent studies suggest even robust demagnetization strategies do not remove the complete drilling-induced magnetic overprint in basement lithologies.

Degaussing the drill string via an alternating-field coil mounted beneath the rig floor was attempted during the DSDP. The coil was destroyed fairly quickly during operations and the analysts interpreted that inasmuch as the pipe was exposed to additional stresses on each deployment this was probably a fruitless endeavor.

Theoretical modeling indicates that the magnetic field in a steel core barrel is concentrated around its end. If mechanical stresses associated with the cutting process are largely responsible for imparting drilling-related remanences in the presence of this enhanced magnetic field, this suggests that drilling-induced effects could be significantly reduced by minimizing the use of magnetic materials close to the drill bit. This would allow the core to be cut prior to passing through the field at the end of a normal steel core barrel. Replacing drill string components with nonmagnetic materials has been tested on several expeditions. Recent studies have concluded that restricting the amount of time the core is in contact with the core barrel as well as employing core capture components fabricated from nonmagnetic materials significantly reduces the strength of the drilling-induced remanent magnetization in sediment cores. Nonmagnetic core capture components have been fabricated for advanced piston corer (APC) coring tools; however, similar technology has not been developed for the XCB, RCB, or alternative coring tools.

7.5 Additional Technology Development Applicable to Ocean Crust Scientific Objectives

A few different generations of borehole magnetometers have been deployed during the course of scientific ocean drilling. These tools have, for the most part, demonstrated success but have not been maintained by the drilling programs. Rather they have been third party tools subject to sporadic funding and utility. In addition, a single tool that combines susceptibility and remanent magnetization measurements has not been routinely available to scientific ocean drilling. Recent studies suggest the drilling induced magnetic overprint is not as pronounced in borehole, in-situ measurements in sediment; however, owing to rare instances for deployment, no similar assessment is available for igneous ocean crust settings.

High-temperature water samplers deployed during ODP had a poor history of performance. These samplers were all third-party tools, rarely deployed, and commonly poorly maintained between deployments. Industry has developed hostile environment (max. 200°C) temperature/pressure measurement and water sampling tools, but these tools have a minimum diameter too large to fit through the current drill string. Development of a slim-line equivalent with elevated temperature capability (±350°C) is required for sampling fluids at high-temperature hydrothermal systems in young oceanic crust.

Higher-resolution video feed from the subsea drilling cameras and improved lighting have direct science applications as mapping aids. Accurate directional indication (and eventually control) could improve seafloor visualization and borehole installation capabilities. Pan and tilt capability and directional orientation information can contribute to time conservation and safety during reentries and borehole installations.

Scientific objectives have been defined by the IODP microbiological community over the recent years (e.g. Workshop "Exploring Subseafloor Life with the Integrated Ocean Drilling program http://www.iodp.org/subseafloor-life/, IODP-MI Subseafloor life task force http://www.iodp.org/SLTF/. These are site- or region-specific microbiological studies and a global reconnaissance. Protocols for standard, routine sampling and sample processing of microbiological samples are in progress (Scientific Technology Panel, March 2008, July 2008 and March 2009 http://www.iodp.org/stp/, in particularly for sampling within sediments, but less so for sampling within oceanic basement. The panel recommends careful program attention to their implementation within ocean crust drilling. Specifically, establishment of a minimum legacy measurement protocol for hard rock samples, and assigning responsibility for routine microbiological assays is the minimum requirement. Enhancements include additional analysis-specific sampling and sample processing, advanced contamination testing, and contamination mitigation developments such as contamination-reducing core barrels.

7.6 Deep Crustal Penetration

A common perception among the scientific ocean drilling community is that riser drilling is required for deep penetration. Although this might be true for many environments, some locations have been demonstrated to allow riserless operations to at least 1.5 km below seafloor with no indication that further penetration would be immediately limited. Therefore, technology developments that allow deep penetrations in deep water need to be developed for riserless operations. These technologies include, but are not limited to casing engineering and improving coring tools and techniques.

While the envelope for deep crustal drilling can be pushed further with riser-less drilling, the ultimate goal of full crustal penetration will not be achievable without controlled mud circulation as provided by riser drilling. The ideal location for this ambitious experiment, 21st Century Mohole, is not yet identified, but almost for certain will be located in 4 kilometers or more of water depth. It is therefore imperative, for achieving complete crustal penetration of in-situ, fast spread crust and sampling of the uppermost mantle, that technologies allowing controlled mud-circulation at >4 km water depth will be developed. The panel is encouraged to hear that Japan is planning to supply this technology within the next phase of IODP post 2013.

8. Conclusions and Recommendations/Outlook for IODP activities

8.1 Summary Comments

Our knowledge of the formation and evolution of oceanic crust and shallow mantle is currently undergoing fundamental changes in perspective. Over the past decade, multidisciplinary studies undertaken at a diverse range of sites along the global mid-ocean ridge system are revealing that ocean crust – and the processes that form it, alter it or depend on it for their livelihood– is far more diverse than we ever thought. This diversity in both structure and in the underlying processes presents major challenges to our community.

First among these is redefining our working models. No longer can we view the richness and variety of oceanic crustal structure through a simple prism of fast-versus-slow or Penrose-versus-Hess. Instead, new working models, which are rapidly evolving, recognize both the spatial and temporal complexity of the processes that build and alter oceanic crust. In addition, these new models are increasingly multidisciplinary, reflecting the coordinated efforts of geologists, physicists, chemists and biologists to understand the linkages among seafloor spreading, the deep biosphere, the ocean and the atmosphere. Secondly, there is the daunting problem of tractability. How do we begin to characterize the oceanic crust and shallow mantle – which covers nearly two-thirds of our planet's surface – if the processes that form and interact with it are more diverse than previously conceived?

The thematic review panel discussed these issues in depth. As a general recommendation, we propose that better integrated geophysical, seabed sampling/shallow coring and deep drilling experiments, addressing key and testable hypothesis, must be generated by the community that too often is split along lines of tools (availability), rather than effectively united in experiment design. The barrier for this to happen is interpreted by the panel to lie more in the funding structure of the various tools available, rather in a fundamental split of the community involved. We are encouraged that efforts to redefine our working models are being actively pursued by the community, and that now is an exciting and pivotal time for our field. We also highlight that recent discoveries from IODP drilling are making vital contributions to this effort. The discovery that magmatic accretion contributes to core complex formation, for example, was not imagined prior to drilling the Atlantis Massif. In addition, IODP's proven success at drilling intact crust puts our community on the threshold of a long sought objective – sampling the gabbroic layer of fast-spread crust in situ and thereby allowing us to ground truth a vast wealth of marine geophysical and ophiolite studies. The verification by drilling of the relationship between spreading rate and the depth to the original axial magma chamber, jointly with the discovery of the axial magma chambers originally shallow location in the crust (i.e., thin dike complex), provides other compelling examples of ground truthing geophysical observations and models by drilling.

The panel also notes that in addition to the recent accomplishments made in terms of drilling and recovering important targets, some of them of unexpected and surprising nature, the community involved in these experiments has been multi-disciplinary, productive and innovative in their research on samples obtained. In view of these recent successes and the high level of community engagement, the thematic review panel is confident in recommending strategies that will ensure that IODP studies of oceanic crustal structure and formation continue to make discoveries that advance science.

The recommendations of the panel, which are outlined further below, are as follows:

1) Continue drilling at Site 1256 in fast-spread crust so as to make it through the dike-gabbro transition zone and into what is hypothesized to be more primitive cumulate gabbros typical of gabbroic lower crust within ophiolites.

2) Encourage drilling proposals at fast-spreading ridges that will explore shallow and intermediate depth objectives addressing the spatial and temporal segmentation of key processes as suggested by a growing repository of geophysical and surface data, and which will complement complete crustal penetration (MOHOLE) drilling.

3) Continue studies of oceanic crust formed at slower spreading rates, particularly those expeditions that can address key questions pertaining to new and emerging models for divergent plate boundaries, and the spatial and temporal complexity of such plate boundaries and related processes.

4) Encourage studies that better integrate drilling results with geophysical mapping, pre- as well as post drilling, and thereby allow the information from downhole samples to be targeted and understood in the context of larger-scale features and/or processes.

5) Increase the emphasis of microbiologic studies in drilling of oceanic crust in order to better sample and advance studies of the deep biosphere within mafic and ultramafic rocks at mid-ocean ridge environment with varying spreading rates.

6) Encourage more experiments that address fluxes between the solid earth and the ocean, which would, for example, contribute vital information on the thermal and chemical evolution of Earth. This topic has not been well addressed by previous studies, nevertheless, it presents an opportunity for increasing the impact and relevance of future deep earth sampling objectives.

7) Maintain a vision and commitment to Mission Moho, which has been an essential goal of ocean drilling since its inception, which has developed a subset of specific and important goals over time, and which is attainable with appropriate technology and commitment of resources.

8.2 Fast-Spread Crust

Conceptual models of fast-spreading mid-ocean ridges often assume that magma supply controls segmentation, that asthenospheric transport parallels the spreading direction, that mantle upwelling and melt delivery is symmetric about the rise axis and that crustal accretion is complete within a kilometer or so of the axis of spreading. In this simplistic view, all fast-spread ridge crest processes – including melt delivery from the mantle to the crust, crustal accretion, seafloor volcanic activity and the focusing of seafloor hydrothermalism that supports biologic communities – are symmetric about the rise axis and thus amenable to simple conceptual models (e.g., the Penrose Model; Macdonald *et al.*, 1988; Chen and Morgan, 1990; Korenaga and Kelemen, 1997). Recent geophysical studies of the East Pacific Rise, however, provide compelling evidence of large-scale skew and asymmetry of mantle upwelling beneath the ridge axis as well as evidence for the off-axis delivery of mantle melt and the off-axis accretion of crust by intrusive magmatism (Toomey *et al.*, 2007; Toomey and Hooft, 2008). These surprising discoveries are renewing the debate over the origin and significance of spreading-center segmentation (Singh and Macdonald, 2009; Toomey *et al.*, 2009) as well as the processes that control the architecture of oceanic crust and the Moho transition zone and that link mantle upwelling to seafloor volcanic, hydrothermal and biologic activity.

The thematic review panel discussed these recent findings as well as the known variations in ridge morphology, tectonic segmentation (e.g., transforms, overlapping spreading centers and propagating rifts) and seafloor geology. Our discussions emphasized that the architecture and processes of fast-spread crust are by no means uniform and that this lack of uniformity presents an opportunity for the drilling community to generate and formulate proposals that address the new wealth of data generated by ridge-related research. The panel recommends that the community develop drilling proposals that target fast-spread crust and that address key issues, such as the spatial and/or temporal variability of processes related to segmentation. We anticipate that these proposals will have shallow and intermediate depth objectives and that such drilling will complement efforts to obtain complete crustal penetration (MOHOLE).

With regards to recent IODP expeditions, the successful drilling at Site 1256, in the Guatemala Basin, places the earth science community on the threshold of a major advancement in our understanding of the formation of fast-spread crust. To fulfill this promise, Hole 1256D must be deepened. Currently, Hole 1256D touches the dike-gabbro transition zone. But it has not yet penetrated into the hypothesized type of lower crustal, more primitive cumulate gabbros representing the magma reservoirs from which melt to generate the upper crust was delivered. Extending the depth of Hole 1256D to achieve this coverage would dramatically increase the scientific leverage of this site, and the comparative studies with ophiolite sections (see Section 6.2).

If this were to be accomplished before end of the current phase of IODP, the program could declare significant victory on its mission to understand the structure of fast-spread crust and how it compares to the Penrose ophiolite model and thereby demonstrate progress towards full crustal penetration (21st century Mohole Initiative of the ISP). However, Hole 1256D was not initiated and cased with full crustal penetration in mind. The optimum site location and hole design for such an experiment remains to be determined.

8.3 Crust in Other Settings

We now know that at slower spreading rates a profound degree of complexity and variability exists in the magmatic, tectonic, hydrothermal and biologic processes that accompany crustal formation and evolution. That oceanic crust formed at slower spreading rates cannot be simply summarized implies that no single drilling effort can adequately address the complexity of the system. Instead, advancing our understanding of the crust and shallow mantle formed at slower spreading rates will require multiple efforts at sampling in combination with geophysical studies.

Having acknowledged that slow-spread crust is complex, the review panel does note that there are several fundamental discoveries emerging from drilling that taken in the broadest sense suggest that we are on the verge of hypothesizing radically new structures of divergent plate boundaries and modes of seafloor spreading, in which a rolling hinge fault, at least locally, may provide the de facto plate boundary. However, quite unexpected, this type of spreading is not as amagmatic and entirely tectonic in nature as has been hypothesized. Instead, the magma generated by decompression melting of (slowly) rising asthenosphere is for a large part usurped by more shallow mantle, where it both impregnates and alters mantle lithologies, and forms discrete gabbroic intrusions with multiple infusion of melt.

The thematic review panel applauds the profound and possibly paradigm changing discoveries made by in the slow-spread crust in the Atlantic by late ODP and IODP drilling. However, the panel also realizes the enormity of the task ahead to take this these exploratory findings to a new and higher level. Furthermore, deep crustal drilling in these environments necessarily will be restricted to a limited number of sites, even at decadal scale. We therefore concede that the best way forward is to encourage the community at large to develop multi-tool experiments in which geophysics, seabed sampling and mapping, shallow coring and eventually deep drilling can address key questions pertaining to the spatial and temporal complexity of this type of crust and the processes by which it forms. The drilling strategy will vary depending on the mission objectives, e.g. drilling long sections of the lower crust in different tectonic windows versus distributed shallow holes in order to understand the lateral variability in crustal architecture at the scale of a second order ridge segment.

8.4 Deep Biosphere

The thematic review panel emphasized the importance of encouraging more detailed microbiological studies and incorporating these as a routine component of future drilling efforts in the oceanic crust. Although close collaboration of microbiologists with geochemists and geologists has become more customary in regional studies within the RIDGE and InterRidge communities, similar studies and scientific expertise during past drilling attempts have been limited. For example, to date no microbiological data are available from Site 1256 or from the sites drilled during Leg 209, and results of microbiological studies from drilling the Atlantis Massif remain limited. However, the preliminary studies of Mason *et al.*(2008) on the Hole U1309D drill core and studies by Brazelton *et al.* (2006) on the Lost City hydrothermal systems highlight the striking contrast in species, diversity, and abundance of microbes in carbonate chimneys and nutrient-rich fluids resulting from active serpentinization of the oceanic lithosphere compared to apparently more barren gabbroic domains less influenced by hydrothermal activity. These studies, as well as others focused on ultramafic environments, also emphasize that reduced volatiles produced during serpentinization may support an extensive, deep biosphere in portions of the lithosphere that are dominated by ultramafic rocks (Kelley *et al.*, 2005; Perner *et al.*, 2007; Proskurowski *et al.*, 2008). The recent discovery of volcanoes in arc environments hosting molten pools of sulfur with unique hydrothermal vents and biological systems also highlights that there is much is left to be learned about the deep biosphere in these essentially unexplored portions of the oceanic lithosphere.

The highly heterogeneous architecture of the oceanic crust at different spreading rates implies that highly diverse environments are available for a deep biosphere in rocks that make up over 50% of the Earth's crust. Future studies will need to be guided by clear technological support from IODP and established scientific experts to address important questions regarding:

1) The nature and diversity of the biosphere in the oceanic lithosphere formed in different spreading environments, and how these differ in a) volcanic versus gabbroic or serpentinized domains and b) domains influenced by different degrees of hydrothermal activity.

2) How microbial communities change with aging and evolution of the crust.

3) Quantification of biomass in these environments and their preservation through the life cycle of the ocean crust.

4) Quantification of sub-seafloor environmental niches (rock-fluid chemistry, temperature) with specific linkages to microbial assemblages and biomass.

8.5 Global Fluxes

An important goal of geophysical, geochemical and petrological studies of the oceanic lithosphere is to estimate global heat and chemical fluxes in order to understand the long term evolution of Earth's interior as well as its hydro- and biosphere. The thematic review panel acknowledged that this goal is ambitious and remains only partially achieved through past drilling efforts. The panel also identified a number of important questions in which future ocean drilling and related research can make a valuable contribution, for example:

1) What is the flux of heat, mass and volatiles out of the Earth's interior to its crust, mantle, and oceans?

2) What role does ocean crust and exposed mantle play in modulating the chemistry of the oceans and atmospheres through hydrothermal and weathering processes?

3) What is the role of alteration and weathering processes in carbon sequestration?

4) What is the final composition of the lithosphere recycled into the mantle at subduction zones?

All of these questions require a full understanding of the composition and variability of the ocean crust, and the interactions between the crust and oceans on a global scale. This can only be achieved by a combination of drilling, seafloor studies and geophysical mapping.

8.6 Mission Moho

Scientific ocean drilling became established as an offshoot of the ambitious quest in the late 1950s to sample the seismic Mohorovičić discontinuity (Moho) below the ocean floor, the shallowest (in situ) location in which it can be found. Now, 50 years later, this goal remains a high scientific priority, albeit for a number of reasons that were not even thought of back then. The modern scientific rationale for a mission to drill through the Moho was documented in a major international workshop (http://www.iodp.org/mission-moho-workshop/). Following the workshop, a concrete proposal (Mission Moho) was submitted to the IODP, gained high scientific recommendations, but failed to receive program support within the current phase of IODP. One important reason for this failure being the request for a 4 km+ deep water riser capability to support such an ambitious borehole (~6 km in around 4 km of water depth). Development of this deep water technology is now considered by the IODP partner Japan for the post 2013 time frame. The existing *D/V Chikyu* will be capable of deploying such a system and the 10 km+ drill string necessary to achieve this deep target, and thereby for the first time making this ambitious goal a realistic possibility.

The review panel does not feel in a position, or for that matter, mandated to either recommend or reject such an enormous scientific endeavor. However, we did discuss the potential of recent findings achieved by late ODP and within IODP to impact an assessment of a Mission Moho. We here would like to provide specific comments:

1) The findings at Site 1256 position the program to make an important step towards the ultimate goal of a Mission Moho. A moderate deepening of this site has the potential to establish a critical link to gabbroic crust found within ophiolites.

2) The findings from slow spread, dismembered crust (i.e. ODP Leg 209, IODP Expeditions 304 & 305) illustrate the enormity of lateral variation within ocean crust, and have proven exceptionally educational in terms of comparative studies of ophiolites, and their potential bearings on ocean crust formation.

3) The combined lessons from 1 and 2 above is that truly concerted efforts involving marine geophysics, ocean drilling and land studies of ophiolites are needed in order to enable a higher level of understanding of the nature of the crust that covers 2/3 of the planet's surface, and the dynamic processes forming the ocean basins. A deep reference hole sampling the entire crust and the upper most part of the mantle remains in view of the recent ODP and IODP discoveries a pivotal target in a concerted mission to understand formation and structure of the ocean crust and lithosphere.

4) The panel strongly recommends that IODP be honest with the ocean crust community in terms of the programmatic commitment of time and engineering to this kind of research. Designing the most efficient drilling efforts for such a challenging environment cannot be done in a vacuum, and may, without realistic guidelines, lead to poorly spent resources and/or disengagement of scientific community.

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Acronyms

ADCB – Advanced Diamond Core Barrel

APC – Advanced Piston Corer

DIMO – Drilling-Induced Magnetic Overprint

DSDP – Deep-Sea Drilling Project

EPR – East Pacific Rise

HFSE – High Field Strength Elements (Zr, Nb, Hf, Ta)

HRRS – Hard Rock Reentry System

IODP – Integrated Ocean Drilling Program

IODP-MI – Integrated Ocean Drilling Program Management International

ISP – Initial Science Plan

MAR – Mid-Atlantic Ridge

mbsf – meters below sea floor

MORB – Mid-Oceanic Ridge Basalt

OCC – Oceanic Core Complex

ODP – Ocean Drilling Program

RCB – Rotary Core Barrel

RIDGE – Mid-Ocean Ridge Program, RIDGE 2000

SASEC – Science Advisory Structure Executive Committee

SPC – Science Planning Committee

WOB – Weight on Bit

XCB – Extended Core Barrel