IODP Expedition 360: SW Indian Ridge Lower Crust and Moho

Site U1473 Summary

Background and Objectives

IODP Expedition 360 constituted Leg 1 of the SloMo Project, a multi-phase drilling program that aims ultimately to drill through the Moho seismic discontinuity at a slow-spreading mid-ocean ridge. The overall goal of SloMo is to test the hypothesis that the Moho may represent an alteration horizon such as a serpentinization front rather than the boundary between igneous crust and the mantle. If correct, the latter could lie at any depth above the seismic boundary; furthermore, because serpentinization is a methanogenic process, it raises the possibility that a significant biosphere exists below the crust at slow spreading ridges.

The site chosen for this endeavor is Atlantis Bank, an oceanic core complex on the Southwest Indian Ridge proven from previous drilling to expose a substantial section of gabbro (e.g., Dick et al., 1991a, 2000; Pettigrew et al., 1999), and local areas of serpentinite (MacLeod et al., 1998), and beneath which a Moho reflector is present at ~5.5 km below the seafloor (Muller et al., 2000). Phase I of SloMo is to drill 3 km through lower crustal gabbros and to penetrate the inferred crust-mantle boundary; Phase II proposes using the Japanese riser drill ship *Chikyu* to drill to 6 km through the Moho itself and into the mantle.

The principal aim of Expedition 360 was to establish a legacy hole at Atlantis Bank suitable for deep penetration (now Hole U1473A), and then to drill as deep as possible into the lower crustal gabbro layer. By so doing Expedition 360 could in its own right address a number of first-order scientific questions about the mechanisms of accretion of the igneous lower ocean crust and exhumation by oceanic detachment faults. By comparing the results of Expedition 360 drilling with those from prior ODP drilling on Atlantis Bank (Holes 735B and 1105A) we had the opportunity to examine for the first time the lateral continuity of igneous, metamorphic, and structural stratigraphy on a kilometer scale, and hence to assess the spatial and temporal scales of magmatic accretion of the plutonic lower crust and the mechanisms by which it is exhumed. A further aim was to determine the nature of magnetic anomalies in the lower crust by drilling through a magnetic reversal boundary that dips southwards beneath Atlantis Bank. In addition, by employing modern protocols for obtaining samples free from contamination, we aimed to determine the microbiology of the lower ocean crust and hence explore the extent to which life exists in the subseafloor.

Operations

Expedition 360 had 61 operational days (30 November 2015 to 30 January 2016). The expedition achieved the deepest igneous rock penetration from the seafloor on a single *JOIDES Resolution* expedition to date (789.7 mbsf) and recovered 469.4 m of core (59% recovery over entire interval). The sequence of operational events can be grouped into eight successive episodes.

1. Port call and transit to Site U1473 (30 November–16 December)

Expedition 360 spent the first 5.6 d in port in Colombo, Sri Lanka, to offload and load samples, equipment and supplies. The 2817 nmi transit from Sri Lanka to Site U1473 took 10.9 d.

2. Seafloor survey and installing the reentry system (17–19 December)

We established a reentry system using a drill-in casing assembly with mud motor and underreamer, and completed it with a free-fall funnel, at a water depth of 710.2 m. Following a 1.0 d seafloor survey to select the exact drill site, the method and design used for the Site U1473 reentry system took only 1.5 d to install. The drilled depth is 9.5 mbsf, the casing extends to 7.4 mbsf, and the top of the cone is at 703.2 mbsl (7.0 m above seafloor). The casing was not cemented into the hole and the reentry installation proved stable throughout the expedition.

3. First coring episode and three RCB roller cones lost (19–30 December)

During this successful 10.3 d coring episode (including 0.6 d waiting on weather) we retrieved Cores U1473A-2R through 44R (9.5–410.2 mbsf) with a recovery of 207.0 m (52%), using four RCB drilling bits. Projecting the advance per day of this episode (including waiting on weather) to the total remaining coring time, we would have reached a total depth of >1200 mbsf.

4. Fishing for RCB roller cones and medical evacuation (30 December–7 January)

Three RCB bit roller cones were lost in problematic coring conditions at the end of the previous episode, while cutting Core 44R. We made a total of four fishing attempts, first with two fishing magnet runs, then with two Reverse Circulation Junk Basket (RCJB) runs, for a total of 2.8 d, without recovering any cones. However, to everyone's surprise, the last RCJB run recovered an unprecedented 0.5 m long, 18 cm diameter core (Core U1473A-45M; 410.2–410.8 mbsf). This made it extremely unlikely that we had a roller cone left at the bottom of the hole and we decided to resume coring.

Between the first and second fishing run, we sailed to a helicopter rendezvous site near Mauritius for a medical emergency. The 1320 nmi round-trip consumed 5.5 d of operational time.

5. Second coring episode and two more roller cones lost and found (7–12 January)
Cores 46R-55R (410.8–481.7 mbsf) were retrieved with a total recovery of 20.0 m (28%). Penetration rates were high, recovery was low, and cores were highly fractured indicating a weak (faulted) formation. Due to excessive torque, and the need for a wiper trip and reaming the hole, we decided to retrieve the drill string and discovered that the RCB bit was missing one of its four roller cones. The second of two RCJB fishing runs that followed recovered a missing roller cone (leaving a total of three lost cones unaccounted for). We decided to resume coring; however, Cores 53R through 55R (469.6–481.7 mbsf) had zero recovery. Deployment of depluggers had no effect. We retrieved the drill string and found that the bit had damage attributable to a roller cone. We deployed the fishing magnet and recovered one heavily abraded roller cone that had evidently been stuck in the center of the drill bit and so prevented advance and recovery.

6. Drilling ahead (12–13 January)
We decided to drill ahead without coring for an interval not to exceed 100 m using a tricone bit, which is more robust than the RCB coring bit and therefore more suitable to mitigate potential issues near the bottom of the hole, such as reaming a slightly tight hole. We also wanted to get an idea of how much faster drilling would deepen the hole compared to coring. We drilled ahead 481.7–519.2 mbsf (37.5 m), found that the advance rate was not greater compared to that of coring, and after 1.3 d decided to resume coring.

7. Third coring episode (13–23 January)
During this coring episode of 9.9 d (including 0.6 d when the pipe was stuck in the hole at 651.9 mbsf) we retrieved Cores 57R through 89R (519.2–789.2 mbsf) and recovered 241.4 m (89%), using four RCB coring bits. Coring conditions were ideal for the most part in these less deformed gabbroic rocks. We recovered our longest continuous piece of

igneous rock (>3 m) in Core 84R. On 18 January the drill string got stuck in the hole and it took 15 h to get back into coring operations. Nevertheless, extrapolating the average daily advance of this episode (including stuck time) over the total number of coring days available, we would have reached >1200 mbsf.

8. Successful logging and mechanical bit release part lost (23–30 January)

We conducted successful wireline logging runs with (1) the triple combo tool string, (2) the FMS-sonic tool string, and (3) the Ultrasonic Borehole Imager (UBI). When the drill string was recovered, the mechanical bit release (MBR) top connector was missing the sleeve retainer ring, which was presumed to have fallen into the bottom of the hole. We first used a fishing magnet trying to recover the ring, without success. Next we deployed a coring bit in the hope that the missing part may have dropped onto the seafloor when the previous RCB bit was released prior to logging; however, we immediately experienced excessive torque that was attributed to contact with metal at the bottom of the hole. The presence of the sleeve retainer ring at the bottom of Hole U1473A was confirmed with a subsequent RCJB deployment, which recovered three rounded boulders with tool marks that match the dimensions of the sleeve retainer perfectly. At this point in time we had to leave Site U1473 and get underway for Mauritius.

Principal Results

Igneous petrology

During Expedition 360, we recovered 89 cores in Hole U1473A. These are mainly composed of gabbros, with minor diabase dikes and felsic veins. Eight lithological units were defined on the basis of changes in mineral modes, grain size, and texture, together with the presence of other igneous features such as layering and the occurrence of felsic material (either patchy or in the form of veins). Both magnetic susceptibility and geochemical variations were also considered in defining these units. Primary magmatic textures of gabbros down to ~400 mbsf are mostly erased by intense crystal-plastic deformation; when preserved, primary textures are mostly subophitic and locally granular. The main lithology is dominated by olivine gabbro (77.7%), followed in abundance by disseminated-oxide gabbro (9.7%; oxide content between 1% and 2%), gabbro (*sensu stricto*; 5.2%), oxide gabbro (3.7%; oxide content >5%), and oxide-bearing gabbro (3.7%; oxide content between 2% and 5%). Oxide abundance decreases slightly downhole, with exception of the lowermost intervals within which a larger proportion of oxide-bearing lithologies were recovered. Oxide-bearing gabbro and oxide gabbro are usually characterized by a strong localized crystal-plastic deformation; however, in contrast, those in the deepest part of Hole U1473A (Unit VIII) are essentially undeformed. Formation of oxide gabbro is most likely related to the percolation of late-stage melts through an existing olivine gabbro framework, an inference that is supported by the near-ubiquitous presence of interstitial brown amphibole and rims around clinopyroxene and/or olivine. When located around olivine, brown amphibole is also associated with orthopyroxene rims. These late-stage melt related features are less abundant in fresh and undeformed samples from the deeper levels of the hole. Felsic veins comprise ~1.5% of the hole. They consist of leucodiorite, quartz diorite, diorite, trondhjemite, and rare tonalite, locally containing oxide minerals.

Several dikes were found at various depths in Hole U1473A. They intrude gabbroic rocks that had experienced crystal-plastic deformation under conditions ranging from greenschist up to granulite facies. The granulite facies dikes contain an assemblage of granoblastic brown amphibole, plagioclase, clinopyroxene, and orthopyroxene, reflecting recrystallization temperatures likely in excess of 800°C. From textural relationships some dikes appear to have locally partially melted the adjacent gabbro to form the felsic veins.

Olivine gabbro is dominantly coarse-grained and may locally display variability in grain size ranging from fine- to very coarse-grained. Grain size variations are mainly associated with irregular domains with sutured contacts; however they may locally be associated with igneous layering. Igneous layering is well developed in Units II and VII (i.e., 91–175 mbsf and 578–642 mbsf, respectively). In most cases, contacts between different layers are subparallel to each other, though less commonly irregular contacts are also found. Grain-size variability in the layering is generally also accompanied by modal variation.

Hole U1473A displays several similarities with the other two holes drilled at Atlantis Bank (Holes 735B and 1105A; Dick et al., 2000; Casey et al., 2007). Similar igneous processes may have been acting in the genesis of the plutonic section as a whole. Most striking is the first-order observation that the plutonic sections at ODP Hole 735B and IODP Hole U1473A are mainly composed of olivine gabbro (>75%), with numerous intercalations of gabbros containing oxides (~15% of the sections). Intensely deformed and/or oxide-rich intervals are present at the shallowest levels of Holes 735B and 1105A but are less obvious at the top of Hole U1473A, where oxide gabbros are sparsely distributed down the section and decrease slightly with depth. This may be related to differential erosion, leading to removal of the shallowest section of the platform at Site U1473. With depth in Hole U1473A the proportion of late-stage hydrous melt, as indicated by the presence of secondary brown amphibole around clinopyroxene, also decreases.

Felsic rocks are also documented ubiquitously across Atlantis Bank. These rocks are represented by veins or patches that are reported to be associated with oxide gabbros at Hole 735B (Dick et al., 2000), with olivine gabbro at Hole 1105A (Casey et al., 2007), and are randomly distributed at Hole U1473A. Diabase dikes with characteristic granoblastic textures are also observed at Atlantis Bank. These rocks testify to the intrusion of basaltic melts in a relatively hot gabbroic body and imply the occurrence of melt bodies deeper in the section. At Hole U1473A dike margins are invaded by felsic melts that were most likely generated by hydrous anatexis of the previously hydrothermally altered host gabbro. The injection into the crystallizing gabbros of primitive melts that subsequently crystallized as troctolite or troctolitic gabbro is only observed at Hole 735B.

Another common feature of the three holes drilled at Atlantis Bank is the occurrence of 100–400 m thick igneous lithological units defined by variations in texture, grain-size, mode, and geochemical composition. These are mirrored by variations in whole-rock geochemical compositions, which reveal apparent upward-differentiating geochemical trends, as defined by decreases in Mg#, Cr, and Ni contents and increases in Y (see Geochemistry section below). Each of the lithologic units is in turn characterized by an internal heterogeneity in composition and texture on a meter-scale, also documented in the other gabbroic sections sampled at Atlantis Bank. This heterogeneity was likely governed by a complex interplay between magmatic processes (new melt injections, fractional crystallization, melt-rock reaction, and late-stage melt migration) and deformation. In addition, the late-stage evolution of the crystallizing mush appears to mostly occur under hydrous conditions.

Taken as a whole, the igneous stratigraphies of ODP Holes 735B and 1105A, and IODP Hole U1473A document similar processes occurring in all three locations over a lateral scale of >2 km and vertical scale of ≥1.5 km. This leads us to suggest that this portion of the Atlantis Bank plutonic section is relatively homogeneous laterally. Key features are (i) the occurrence of olivine gabbro as the principal lithology, (ii) the ubiquitous presence of disseminated-oxide, oxide-bearing, and oxide gabbros and their greater abundance at the shallower structural levels, and (iii) the presence of ~100–400 m thick olivine gabbro units showing upward differentiating geochemical trends that may represent discrete magma bodies. Whereas the different drill holes display striking similarities between each other overall, we do not attempt to correlate igneous units directly from hole to hole; instead we prefer to emphasize the similarity in overall igneous accretion processes during oceanic core complex formation.

How applicable are the conclusions we draw from drilling at Atlantis Bank to other oceanic core complex gabbro massifs, or indeed to plutonic accretion processes at (slow-spreading) mid-ocean ridges in general? In partial answer to this question we may compare the igneous architecture documented at Atlantis Bank with that of the gabbro body drilled at Atlantis Massif, the oceanic core complex at 30°N on the Mid Atlantic Ridge (IODP Hole U1309D; Blackman et al., 2006, 2011). The most striking difference is related to the lithological variability of the two sections. In particular, Atlantis Bank is dominated either by olivine gabbro or oxide-bearing gabbro (only), whereas Atlantis Massif contains a much broader range of lithologies, ranging from troctolite through to olivine gabbro to gabbro and oxide gabbros, but dominated by gabbro (*sensu stricto*). An even more significant difference is the presence of relict mantle peridotite horizons, and olivine-rich troctolite formed by reaction of mantle peridotite and basalt melt (e.g., Drouin et al., 2009), as well as minor dunite between the gabbro bodies at Atlantis Massif, a feature that was not observed at Atlantis Bank. The observation of these important differences in the igneous stratigraphies lead us to conclude that significant variability exists in the mode of accretion and internal differentiation of magmatic bodies in the lower crust between oceanic core complexes, likely reflecting variations in spreading rate, magma supply, and tectonic setting along ocean ridges.

Geochemistry

The lithologies examined from Hole U1473A are dominated by moderately evolved olivine gabbro with Mg# between 82 and 66. Mg# covaries with other petrogenetic indicators such as Ca#, Ti, Y, Cr, and Ni. The variation in Cr and Ni concentration cannot be explained by modal mineralogy, but is attributed to the composition of pyroxene and olivine in the rock.

Downhole variation plots show major discontinuities in Mg#, Cr, Ni, and Ca# at ~60–90 mbsf, 300 mbsf, and ~700 mbsf. The discontinuities are interpreted as defining upwardly evolving units of magma intruded in individual intrusive events. However, oxide gabbros occur in centimeter-scale intervals throughout the section and are significantly more evolved than the background olivine gabbro, providing evidence for the migration of late-stage melts over minimum distances of tens to hundreds of meters.

The average composition calculated for Hole U1473A is indistinguishable from that of Hole 735B, with Mg# of 71 ± 3 wt% and TiO_2 of 0.7 ± 0.2 wt%. The average composition of the Atlantis Bank gabbros overlaps with compositions from Atlantis Massif (Hole U1309D; Godard et al., 2009), if slightly more evolved. However, they are both substantially more fractionated than the bulk lower crust average calculated for Hess Deep (fast-spread lower crust; Gillis et al., 2014). This difference might be related to the volume of magma separated from the gabbroic (cumulate) section of the crust by diking and extrusion. We propose that less melt is able to be extracted from magma bodies that are emplaced into detachment fault footwalls and rapidly exhumed at slow-spreading ridges (MacLeod et al. 2009); hence gabbroic units retain compositions closer to that of the primitive melt. In any case, the slower upwelling rate at slow-spreading ridges would be characterized by greater conductive heat loss from the lower crust and hence faster cooling inhibiting melt loss by comparison to fast spreading ridges.

Hole U1473A gabbros have H_2O contents of 0.3 to 8 wt%, typical of oceanic gabbros and much higher than expected in pristine cumulates. The abundance of H_2O decreases with depth but measured amounts reflect deep and pervasive infiltration of seawater through the crustal section. Examination of altered and fresh sample pairs indicates that the alteration did not significantly alter major element compositions or the concentration of the trace elements investigated. This is consistent with the infiltration of low-salinity seawater derived fluids with limited potential for mobilizing other elements.

CO_2 is below detection limit in many of the samples investigated, but concentrations of up to 2 wt% CO_2 were obtained for altered rocks in the carbonate-veining zone (~210–470 mbsf). A surprise was that four of the carbonate-rich samples investigated are dominated by up to 0.5 wt% of inorganic carbon rather than CO_2. These high concentrations are similar to the range reported for clay-rich alteration of glass on the seafloor and may be related to clay alteration. The amount of organic carbon present is a factor of 10 higher than determined for the majority of serpentinites investigated previously. This is an intriguing result and may require that low-temperature alteration minerals of gabbro be added to the list of potential microbial habitats in the subseafloor.

Metamorphic petrology

The Hole U1473A gabbros show three distinct modes of alteration: (1) static hydrothermal alteration, (2) alteration associated with crystal-plastic deformation, and (3) alteration associated with cataclastic deformation.

Static background alteration is pervasive, with alteration mineral abundance ranging from <3% to 90%. In some intervals with intense veining, the alteration mineral abundance reaches >90%. Static alteration minerals consist mainly of: (i) colorless amphibole, talc, serpentine, and clay minerals after olivine, (ii) secondary clinopyroxene and brown to green or colorless amphibole after clinopyroxene, (iii) colorless amphibole and talc after orthopyroxene, and (iv) secondary plagioclase and chlorite after primary plagioclase. These minerals occur in different abundances in each core or hand specimen and indicate variable temperature conditions for alteration. Textural relationships document overprinting of lower-temperature over higher-temperature assemblages during the cooling of the gabbroic sequence. The formation of the secondary clinopyroxene and brown amphibole association most likely took place at near-solidus temperatures (>800°C). Brownish green and green amphibole, and tremolite/actinolite + chlorite ± talc assemblages formed at amphibolite to greenschist facies metamorphic conditions (700°–400°C). The assemblage of secondary plagioclase + chlorite + pale-green amphibole (actinolite) with minor amounts of zoisite and titanite indicates greenschist facies conditions (450°–350°C). Serpentinization of olivine most likely took place at temperatures in the range 350°–200°C, i.e., lower than greenschist facies alteration but higher than that of clay mineral formation. Clay minerals are the latest products of alteration at lowest temperatures (<150°C). Downhole trend in background alteration is related to metamorphic vein distribution mentioned below.

Amphibole veins and amphiboles replacing primary mafic minerals are dominant at shallower levels (<180 mbsf), as they are in Hole 735B, whereas carbonate or carbonate-clay veins are conspicuous at 180–580 mbsf. Oxidative reddish clay-mineral replacement of primary minerals is also significant from the seafloor to 580 mbsf. In these intervals, it is common that millimeter-wide veins have alteration halos that are up to centimeters wide. At deeper levels (>580 mbsf), microveins filled with chlorite ± amphibole are more abundant than the millimeter-wide veins.

Felsic veins are typically more altered than host gabbros. The most apparent feature is the replacement of primary plagioclase, and sometimes quartz, by secondary plagioclase, which has a characteristic whitish, milky appearance and often has fluid inclusions. Together with association of a relatively high abundance of secondary sulfide and patches of clay minerals in these veins, this implies that the felsic veins were pathways for large volumes of hydrothermal fluids, as also found in Hole 735B (Dick et al., 1991b), particularly at lower temperatures (subgreenschist facies). Local occurrence of biotite in host gabbros is evidence for metasomatic alteration related to felsic vein intrusion.

Neoblasts formed by crystal-plastic deformation typically consist of olivine, plagioclase, and clinopyroxene with minor brown amphibole and Fe-Ti oxide minerals. This mineral assemblage indicates near-solidus temperature conditions (>800°C). Amphibolite mylonites composed of brown-green hornblende and plagioclase, typically associated with minor Fe-Ti oxides, locally develop in thin discordant mylonitic bands. The amphibolite facies mineral assemblage also occurs in the halos associated with amphibole veins. Amphibolite mylonites and amphibole-vein halos show cooling of the gabbroic sequence to temperature conditions pertaining to the transition from ductile to brittle regime (~700°C).

Intervals recording intense cataclastic deformation have abundant carbonate and brownish clay mineral(s). Clays and carbonates show textural relationships indicative of their simultaneous formation, and some of the carbonates show a signature of plastic deformation. These observations document that cataclastic deformation took place in association with alteration at low temperatures (<150°C).

Structural geology

Magmatic contacts separating the igneous intervals include moderately dipping tectonic (8%) and intrusive (6%) contacts as well as shallow dipping grain size (23%) and modal (25%) contacts; 38% of interval boundaries were not recovered or preserved.

Magmatic fabrics are weak to moderate, form in fine- to coarse-grained intervals, and range in dip from subhorizontal to inclined. Magmatic fabrics are better developed in finer-grained intervals and are commonly associated with grain size layering. The fabrics also form subparallel to magmatic contacts. In many samples the transition from magmatic to crystal-plastic is preserved as a weak to moderate overprint of submagmatic/semi-brittle deformation leading to subsequent crystal-plastic deformation.

Magmatic veins and magmatic breccias account for ~1.5% of the section and consist of diorite (15%), leucodiorite (26%), quartz diorite (23%), tonalite (3%), and trondhjemite (33%). Trondhjemite veins occur mainly at or below 400 mbsf, whereas the other four vein types occur above 600 mbsf. Several vein generations reflect a history of injection during ongoing deformation, during which some veins were deformed and transposed by shearing and others provided a setting for strain localization. Nearly all veins show at least some evidence of deformation and high-/low-temperature alteration; moreover, some have undergone alteration during hydrothermal fluid migration, or as a result of fluid exsolution during the final stages of felsic crystallization.

IODP Hole U1473A has a 600 m thick zone of porphyroclastic to ultramylonitic shear zones. This broad interval of ductile deformation contains two, 10 m thick, high strain intervals near 215 mbsf at its core. Below 600 mbsf, deformation becomes more discrete, consisting of thicker porphyroclastic fabrics cored by mylonites and/or ultramylonites, which are commonly Fe-Ti oxide-rich. The sense of shear is typically normal above 50 mbsf and is predominantly reverse at deeper levels. A comparable transition is also observed in ODP Hole 735B. Crystal-plastic fabrics commonly have amphibole, either within the shear zone or as veins, and in some cases have a brittle overprint.

Seven major fault systems have been identified, ranging from discrete 5 cm thick cataclasites in the top of the hole to a 50 m thick fault zone at 411–469 mbsf. This 50 m thick fault consists of chlorite-rich and carbonate-rich breccias and correlates with an increase in carbonate veining, indicating the presence of a fault-controlled hydrogeological system. Discrete fractures are mainly observed above ~600 mbsf. Multiple slickenlines are observed with a majority of moderate to steep rakes, indicating oblique- and dip-slip movement.

Moderate to steeply inclined amphibole veins are concentrated in the top ~170 mbsf and drastically decrease in abundance below this interval. At 540 mbsf and below, amphibole veins occur sporadically. Horizontal clay veins occur throughout the borehole with a maximum at ~150 mbsf. Moderately to steeply inclined carbonate vein density increases from 210 mbsf downhole, with a maximum at 340 to 400 mbsf. Below 470 mbsf carbonate veins decrease steadily, and they are not present below ~670 mbsf. Incomplete infill of calcite and clay veins, and the correlation of these veins with zones of fracturing, are indicative of low-temperature, potentially recent fluid flow through the fault system.

IODP Hole U1473A is dominated by a thick zone of concentrated crystal-plastic deformation, consistent with exhumation along a detachment shear zone. The crustal column was built at the ridge and started to deform with melt present. The complex relationship between deformation and felsic veins indicates a protracted history of melt generation and deformation. In some cases deformation may have started with the alignment of magmatic minerals that formed an anisotropy on which crystal-plastic deformation nucleated. Ductile deformation continued down to amphibolite conditions where either the fabrics contain amphibole parallel to the foliation, or are cut by amphibole veins that either transpose the fabric or offset it. The crystal-plastic fabrics also have a brittle overprint observed in the upper 275 mbsf. The complex relationship between magmatic fabrics, crystal-plastic fabrics, alteration veins, and brittle deformation attests to the down-temperature deformation path recorded by lower crust during exhumation along the detachment shear zone. The greenschist or subgreenschist facies high-angle normal faults that cut the crustal section in IODP Hole U1473A were responsible for the difficulty in drilling.

Paleomagnetism

Remanence measurements were made on archive section halves from Hole U1473A. This generated demagnetization data at more than 12,000 measuring points downhole. Virtually all intervals have positive inclinations, indicating that the sampled gabbroic rocks hold a reversed polarity magnetization, consistent with the interpretation of marine magnetic anomalies (Allerton and Tivey, 2001) that places Hole U1473A within geomagnetic polarity chron C5r.3r (Gradstein et al., 2012). Moreover, the sampled gabbros carry sufficiently strong magnetizations to account for the observed magnetic anomalies over Atlantis Bank.

The archive section-half data were subject to principal component analysis using a processing and filtering scheme designed to rapidly identify the highest quality, highest coercivity components for subsequent tectonic interpretation. The resulting principal component data allow subdivision of the hole into upper and lower zones with statistically different inclinations. Thermal demagnetization data from discrete samples subject to the same filtering for reliability support this subdivision. The boundary between major inclination zones corresponds to the fault zone observed at 411–469 mbsf, from a mean value of ~72° above 400 mbsf to a mean value of ~61° below 400 mbsf. A narrow zone of steeper inclinations (mean value of 73.3°) is also seen between 737–750 mbsf. Compared to the expected dipole inclination of 51.3°, these results imply a significant but variable rotation of the Atlantis Bank footwall since acquisition of magnetization, with the major change across the fault zone likely reflecting differential rotation across this structure.

Although the greater part of Hole U1473A carries a reversed polarity magnetization, thermal demagnetization of discrete samples and alternating field demagnetization of archive section-half pieces reveals characteristic remanence with negative inclinations in some narrow zones of altered gabbro (around ~564, 678, and 749 mbsf). The presence of these zones within broader intervals of reversed polarity indicates (near-) complete remagnetization of these rocks during a subsequent normal polarity period. The timing of the alteration cannot be uniquely determined from these data, but the presence of these components in the lower part of the hole suggests that the reversal boundary between reverse geomagnetic polarity chron C5r.3r and normal polarity chron C5r.2n may occur in close proximity to the current bottom of Hole U1473A.

Petrophysics

Core sections were measured in data loggers for magnetic susceptibility, gamma ray attenuation density, and natural gamma radiation. Magnetic susceptibility was measured on both whole-round sections and archive halves, using a pass-through sensor coil and a contact probe, respectively. The measured magnetic susceptibility varies over the whole instrument range (10,000 instrument units, i.e., ~0.1 SI); high magnetic susceptibilities (>1000 instrument units) are related to abundant magnetite in gabbroic lithologies. The dominant olivine gabbro lithology has relatively low susceptibility that does not exceed a few hundreds of instrument units. At the centimeter to decimeter scale, high values of magnetic susceptibility indicate oxide-rich intervals, seams, and patches.

Natural gamma radiation from the gabbro cores is consistently very low (≤1 cps). Several isolated peaks up to ~10 cps were observed at narrow felsic intervals. In the lower part of the hole, below ~575 mbsf, these narrow peaks often correlate with the highest magnetic susceptibility signals, indicating the presence of magnetite in felsic melts.

Gamma ray attenuation density estimates range from 2.1 to 3.2 g/cm^3, and average ~2.65 g/cm^3. Estimates are slightly less variable in the bottom of the hole, below the major fault zone at ~411–469 mbsf, than in shallower sections, with average value about 2.67 g/cm^3.

Density and porosity were determined for 186 samples. Grain density ranges from 2.88 to 3.13 g/cm^3, and averages 2.98 g/cm^3. It does not vary significantly downhole, except for a slightly higher variability above the major fault zone at ~411–469 mbsf. Porosity is generally very low; it ranges from 0.1% to 4.2% and averages 0.6%.

Compressional seismic velocity was measured at room pressure and temperature along three perpendicular directions on 2 × 2 × 2 cm cubic samples. Of the 184 gabbroic samples measured from Hole U1473A, 94% were olivine gabbro. V_p ranges from 5930 to 7150 m/s, with an average value of 6734 m/s, and an average standard deviation of 25 m/s. Above the major fault zone at ~411–469 mbsf, V_p shows a modest increasing trend over the interval ~280 to ~400 mbsf, from ~6700 m/s to ~7100 m/s. This progressive increase does not continue deeper in the hole; below the major fault zone, V_p is lower on average (6646 m/s) than in the upper part of the hole (6795 m/s), with a similar range of local-scale variability. Local trends of decreasing V_p over a few tens of meters match trends of increasing porosity and correspond to more fractured intervals and fault zones. The measured apparent anisotropy of V_p is generally low, ranging from 0.1% to 10.9%, and averaging 2.2%; the slowest average V_p of the three measured directions is parallel to the core axis (~6708 m/s).

Thermal conductivity was measured on 86 samples from archive section halves. It ranges from 1.77 to 2.52 W/(m·K), and averages 2.28 W/(m·K). The standard deviation of the measurements is <2% (0.66% on average). Olivine gabbro conductivities are in the same range as those measured on previous oceanic crust drilling expeditions. Below ~450 mbsf, the average thermal conductivity is slightly higher (2.36 W/[m·K]) than in the upper part (2.21 W/[m·K]). This may partly reflect the general change in background alteration at the bottom of the hole; below 560 mbsf, the olivine is less altered and secondary clays are absent.

Downhole logs were successfully acquired at the end of drilling operations using three tool strings: a modified triple combo (natural gamma radiation spectroscopy, bulk density, bulk resistivity, and magnetic susceptibility), an FMS/sonic string (seismic velocity, electrical resistivity imaging), and an ultrasonic string (acoustic imaging). Each tool string also measured total natural gamma radiation and borehole temperature. The borehole diameter measured by the triple combo tool string shows significant variations in the upper part of the hole, down to ~560 mbsf, and a much more regular and smooth borehole below that depth, where core recovery averaged 90%. Intervals where the hole diameter is very variable and/or out of gauge correspond to low recovery and/or faulted material identified in the core. The presence of fault zones at ~411–469 mbsf is indicated by low electrical resistivity and low bulk density. A negative temperature excursion recorded by the temperature tool on each run also places the base of a major fault that appears to introduce colder fluid into the borehole at ~469 mbsf.

In the bottom part of the hole, below 560 mbsf, V_p is about 6840 m/s on average, significantly higher than above that depth, where it is generally about 6300 to 6400 m/s away from fault zones.

Microbiology

Microbiology sampling during Expedition 360 was focused on exploring evidence for life in the intrusive crust and hydrated mantle using culture-based and culture-independent approaches, microscopy, and enzyme assays. Sampling efforts were focused on cores with evidence of alteration or fracturing within all lithologies encountered. In total, 68 whole round samples (4–22 cm long) were collected for microbiological analysis. ATP was quantified from all samples and ranged from below detection to 5 pg cm^{-3} (mostly <1 pg cm^{-3}), indicating the presence of a subsurface biosphere in Atlantis Bank. Samples collected for postcruise research include fixed samples for cell counts to quantify microbial biomass, and frozen samples for DNA, RNA, and lipid extraction to describe the diversity (DNA, lipids) and activity (RNA) of the microbial community. Thirty-eight samples were inoculated into up to ten different kinds of microbial media targeting specific prokaryotic iron-reducing microbes, sulfate-reducing bacteria, sulfur-oxidizing microbes, archaeal methanogens, and eukaryotic fungi. These will be analyzed during postcruise research. In addition, for 12 samples we established nutrient addition experiments testing nutritional constraints on microbial biomass in this environment. Enzyme activity assays were conducted using substrates for alkaline phosphatase, leucine aminopeptidase, and arginine aminopeptidase at fifteen sample depths in Hole U1473A. These experiments are ongoing, but initial analysis indicates the presence of very low alkaline phosphatase activity, whereas enzyme activity for both peptidase substrates was below detection. Finally, a new microbial contamination tracer, perfluoromethyl decaline (PFMD), was used for contamination testing for the first time. PFMD was run during coring operations for ten samples and was routinely detected in the drilling fluids, usually detected on the outside of uncleaned cores, and rarely above detection on the cleaned outside of cores. It was below detection on the inside of cores, indicating that penetration of drill fluids to the interior of whole round drill cores where we collected our samples is unlikely. We ran three runs of the commonly used tracer perfluoromethylcyclohexane (PMCH) at the end of the cruise for comparison. It was more difficult to clean the core exteriors successfully with this more volatile tracer, and PMCH was detected on occasion on core interiors.

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