IODP Expedition 360: SW Indian Ridge Lower Crust and Moho

Site 1105 Summary

Background and Objectives

During the 11 d transit from Colombo, Sri Lanka, to Site U1473 at Atlantis Bank, the Expedition 360 scientific party reexamined the cores drilled during ODP Leg 179 at Hole 1105A (Pettigrew et al., 1999; Casey et al., 2007). This activity involved rigorously describing the cores and many of the accompanying thin sections, with the primary purpose of familiarizing the scientific party with the material likely to be encountered at the new Expedition 360 Site U1473, situated 1.4 km to the north. The scientific party developed templates for the description of the igneous, metamorphic, and structural features of the cores and thin sections to establish core description protocols for the new Site U1473 cores. An additional benefit of redescribing the Hole 1105A cores is that the data generated are in a format directly comparable with those for Hole U1473A.

In general, our findings were very similar to those produced by the ODP Leg 179 scientists; however, with a larger scientific party to work on the cores, some of the information collected is new. We include this information in a separate site chapter of the Expedition Report in the Expedition 360 *Proceedings,* as a basis for direct comparison with the results of drilling at Site U1473. In addition, we were able to make certain physical properties measurements on the Hole 1105A cores, including section half magnetic susceptibility measurements that had not been possible on ODP Leg 179. It is important to note here that the observations made on the Hole 1105A cores by the Expedition 360 scientific party augment, rather than replace, those made by the ODP Leg 179 scientists.

Operations

ODP Hole 1105A (32°43.1346′S, 57°16.6518′E; water depth 702.9 m) was occupied 2–10 May 1998 during ODP Leg 179 (Pettigrew et al., 1999). During ODP Leg 179, the location of Site 1105 was positioned ~1.2 km east–northeast of legacy Hole 735B on the Atlantis Bank platform, far enough from Hole 735B to avoid duplication of the stratigraphy and close enough to use the legacy hole as a geological reference section. Coring in Hole 1105A penetrated from 15.0 to 158.0 mbsf and recovered 118.4 m (83%).

The observations presented here were obtained during IODP Expedition 360, mostly during the transit at the beginning of the cruise from Colombo, Sri Lanka, to Site U1473 (5 December 2015–18 January 2016).

Principal Results

Igneous Petrology

Our observations on the igneous petrology of this section are summarized below and then briefly compared with those made during Leg 179. The 30 cores recovered from Hole 1105A are composed of gabbroic rocks and related felsic veins (Pettigrew et al., 1999; Casey et al., 2007). The gabbroic rocks are mostly coarse-grained, with subophitic to granular textures, and are variably deformed. Subophitic textures dominate in undeformed samples. The main lithologies are oxide gabbro and olivine gabbro, followed in abundance by gabbro (sensu strictu). A significant proportion of the olivine gabbro and gabbro intervals contain small amounts of oxides and are referred to as disseminated-oxide gabbro (1% to 2% oxides), and oxide-bearing gabbro (2% to 5% oxides). On the whole, gabbroic rocks with oxides >1% dominate below 35 mbsf, and they tend to be more plastically deformed than other lithologies. Oxides are particularly abundant and probably crystallized from percolating evolved melts. In these deformed gabbros, oxides are not obviously affected by plastic deformation, and thus apparently crystallized after dynamic recrystallization of the silicates. Some rare undeformed oxide-gabbros are also observed. Thin intrusions of fine-grained olivine gabbro occur between 60 and 75 mbsf. Numerous felsic veins occur throughout the core and are concentrated at 15–60 mbsf and 135–155 mbsf. Detailed observations of the corresponding thin sections allow us to document the evolution of late-stage melts within a crystallizing mush, and to track the origin of magmatic oxide minerals where they are particularly enriched.

When compared with ODP Hole 735B gabbros (Robinson et al., 1989; Dick et al., 1999), Hole 1105A is more enriched in oxide-bearing varieties (disseminated-oxide gabbro, oxide-bearing gabbro, or oxide gabbro), and therefore represents a section of crust that is more evolved overall than that recovered at Hole 735B. The oxide-rich section of Hole 1105A is thicker overall, and more enriched in oxides than the principal oxide-rich portions of Hole 735B (Units III and IV; 170.2 to 274.1 mbsf). Deformation grade and alteration patterns are also different, and a downhole differentiation trend similar to that observed for Hole 735B oxide gabbro is questionable for Hole 1105A whole-rock compositions, but may be more evident when considering mineral compositions (Dick et al., 1999, 2002; Pettigrew et al., 1999; Casey et al., 2007). If the Hole 1105A section is equivalent to any section in Hole 735B, the most likely candidate would be Units III and IV (170.2 to 274.1 mbsf; Casey et al., 2007). Nevertheless, given the mismatch in comparisons presented above, and as discussed in Casey et al. (2007), Hole 1105A may not represent a single layer connected directly with Hole 735B; rather it may instead record the manifestation of a similar process, dominated by the percolation of evolved melts that have the potential to precipitate oxides and concentrate them in high porosity regions located in the shallowest levels of the sections. At Hole 735B, this low porosity level clearly corresponds to units affected by crystal-plastic deformation; such a relation is however less evident at Hole 1105A. The shallowest section of Hole 1105A (from 15 to 40 mbsf) is composed of material that is less evolved (olivine gabbro) and less deformed than in the deeper sections, and is similar to several units recovered lower in Hole 735B. At Hole 735B, most felsic veins are associated with oxide gabbro (e.g., Natland et al., 1991), a relationship that is not observed at Hole 1105A.

When compared with results of Leg 179 (Pettigrew et al., 1999), we have defined fewer intervals: 108 during Expedition 360 versus 141 during Leg 179. Their modal content estimates are on average also quite different to ours, resulting in different proportions of rock types (olivine gabbro, 39% during Expedition 360 vs. 43% during Leg 179; gabbro, 21% vs. 36%, respectively; oxide gabbro, 41% vs. 21%, respectively). Our values as presented above have been adjusted to match Leg 179 descriptions, since during Leg 179 disseminated-oxide gabbro (defined as having oxide content from 1% to 2%), and oxide-bearing gabbros (oxide content from 2% to 5%) were included within the gabbros.

The units defined for Hole 1105A during Leg 179 and Expedition 360 are relatively similar to each other. Four units were defined both during Leg 179 (two subunits in Unit II) and during Expedition 360. The transition between Units I and II are relatively close (<10 m difference), the transition between Unit IIA and IIB of Leg 179, and between corresponding Unit II and III of Expedition 360 also differ by <10 m, and the transition between Unit IIB and III of Leg 179 is 4 m deeper than the transition between Units III and IV of Expedition 360. No distinction was made during Expedition 360 for the deepest part of Hole 1105A, in which a Unit IV was defined during Leg 179.

Metamorphic Petrology

Most gabbros in Hole 1105A (83%) have <30 vol% of secondary minerals formed by static alteration; intervals of extensive static alteration (≥60 vol%) are rare (<3% of the total). The intensity of static alteration shows no trend with depth in the hole. Olivine and plagioclase are generally the most and the least altered phases, respectively. Plagioclase is substantially altered only where the host rock shows intense veining or cataclasis. Felsic veins tend to be substantially more altered than their host gabbros.

High-temperature alteration is largely associated with crystal-plastic deformation. The neoblastic minerals (plagioclase, olivine, and clinopyroxene, the latter locally associated with minor brown amphibole) document crystal-plastic deformation under granulite to upper amphibolite facies conditions. The high-temperature alteration is also locally manifest by the static replacement of magmatic clinopyroxene by secondary clinopyroxene and minor brown hornblende.

Subsequent phases of metamorphism are recorded in veins and by static alteration minerals. Veins filled with brownish green hornblende forming up to 1 mm long crystals are presumed to have formed under amphibolite facies conditions. Other veins are characterized by pale-green actinolitic amphibole needles associated with chlorite. These veins likely developed under greenschist facies conditions.

The moderate-temperature static alteration minerals vary in conjunction with the primary mineral. In particular, variable replacement modes were observed for olivine. Olivine is commonly altered to talc and minor oxide aggregates, frequently with an outer rim of chlorite where it is in contact with plagioclase. A less frequent mode of olivine alteration is represented by local aggregates of chlorite and pale green amphibole in coronas along plagioclase contacts. Clinopyroxene is altered along rims, cleavage surfaces, and microveins into green to pale-green amphibole. Plagioclase hydrothermal alteration is mostly confined to development of chlorite along the contacts with primary mafic minerals and within microveins, in many instances in association with minor secondary plagioclase.

Abundant veins filled with clay minerals record hydrothermal alteration under oxidative subgreenschist facies conditions. Veins of this type are conspicuous in a few intervals in association with significant cataclastic deformation. In these intervals, olivine and pyroxene are mainly replaced by reddish brown clay minerals or by mixtures of clay and iron oxy-hydroxides. Similar clay and carbonate veins and brownish clay pseudomorphs after olivine and pyroxene occur in host gabbros near the cataclastic zones. Low-temperature carbonate veins are also present towards the bottom of Hole 1105A.

Structural Geology

The distribution and intensity of structures in ODP Hole 1105A—magmatic contacts, veins, and fabrics; crystal-plastic fabrics; alteration veins; cataclastic material and fractures—represent a continuous record of deformation from ductile to brittle. The proportion and overall intensity of gabbroic rocks displaying crystal-plastic fabrics increases downhole, from decimeter-thick discrete mylonites in the top 80 mbsf to meter-thick gneissic porphyroclastic shear zones below 80 mbsf. Intervals of mylonite and ultramylonite, which may overprint earlier magmatic fabrics, are characterized by elongated bands of plagioclase intercalated with bands of pyroxene and are commonly Fe-Ti oxide-rich. Crystal-plastic fabrics are shallowly to moderately inclined and commonly display reverse shear sense, although normal shear sense does occur. Fe-Ti oxides are abundant in many samples ranging from deformed to undeformed, and concentrate near magmatic contacts. Eighty percent of magnetic susceptibility peaks correlate with intervals that contain evidence for crystal-plastic deformation (intensity of $\geq$1).

Magmatic fabrics (shape-preferred primary orientations of elongate crystals) are commonly overprinted and obscured by subsequent, near-penetrative crystal-plastic fabrics. Where magnetic fabrics do occur, they are weakly developed. Typically they are inclined and better developed in finer-grained rocks and near magmatic contacts. Magmatic contacts range from intrusive to gradational and sheared, with the majority of contacts being gradational, defined by grain size or modal variations. Magmatic veins are common throughout the top and bottom of Hole 1105A (0–65 mbsf; 138–158 mbsf) and are absent from the middle part of the section (65–138 mbsf). Most of the magmatic veins crosscut a previous crystal-plastic fabric and are not themselves plastically deformed; however, in a few instances leucocratic gabbroic veins are observed that have a mylonitic overprint. In some cases the deformation is confined to the vein while the host gabbro is apparently undeformed. These intrusive relationships indicate at least two generations of melt input and deformation. The distribution of magmatic vein dips is bimodal, similar to that seen in ODP Hole 735B.

Five fractured zones are identified in ODP Hole 1105A, two of which are fault zones. These fault zones, at 112 and 127 mbsf, are each ~5 m thick fractured intervals surrounding a core of fault breccia. Discrete fractures are generally planar, some with slickensides. The slickenlines have a steep to moderate rake, indicating oblique to dip-slip. The dip magnitude distribution is not random.

Alteration veins vary in orientation as well as mineralogy: amphibole veins tend to be moderately to steeply inclined, whereas carbonate and clay veins are generally subhorizontal. Amphibole veins are most common at 40–50 mbsf, 60–70 mbsf, and 120–130 mbsf, intervals in which other vein fills are rare. Incomplete fill 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 fracture systems. This is consistent with measured downhole logging temperature anomalies at 104–105 mbsf and 135–136 mbsf (Pettigrew et al., 1999).

The relative ages, distributions, and orientations of structures, ranging from magmatic contacts to brittle faults, document a down-temperature continuum of deformation, spanning the entire history from magmatic accretion to exhumation. Perhaps the most striking observation is the absence at Hole 1105A of a coherent, high-strain porphyroclastic to mylonitic shear zone at the seafloor directly comparable to that documented at Hole 735B, 1.2 km to the east–northeast (Robinson et al., 1989; Dick et al., 1991). Given the generally accepted interpretation of Atlantis Bank as an oceanic core complex, the apparent absence of detachment fault shearing at the surface of the platform might best be explained by erosion following the earlier uplift of Atlantis Bank to sea level. Erosion might also explain the absence of a significant brittle overprint at the top of the hole. Most likely, the high-temperature deformation exhibited in ODP Hole 1105A represents the deeper part of the damage zone of the detachment shear zone below the ridge axis.

Paleomagnetism

Remanence measurements were made on archive section halves from Hole 1105A. These had previously been demagnetized at a maximum field of only 20 mT during Leg 179;

hence during Expedition 360 we were able to conduct further stepwise demagnetization up to 50 mT. We thereby generated demagnetization data at more than 2500 measurement points downhole. These data were subject to principal component analysis using a processing and filtering scheme designed to rapidly identify the highest quality demagnetization data for subsequent tectonic interpretation. Piece-averaged principal components have a mean inclination of 72.5° (determined from 346 archive section half pieces). This value is in good agreement with those obtained previously at ODP Site 753B (71.1°) and from seabed rock drill samples (Allerton and Tivey, 2001). Compared to the expected dipole inclination of 51.3°, the results imply a consistent minimum rotation of the Atlantis Bank footwall of ~20° since acquisition of magnetization.

Petrophysics

New measurements of physical properties on section halves and section-half pieces from Hole 1105A were acquired and integrated with the new shipboard core descriptions. Using equipment not available to Leg 179 scientists we measured point magnetic susceptibility on archive halves, and thermal conductivity on discrete samples.

The mean magnetic susceptibility of rocks recovered in Hole 1105A is 1800 instrument units (i.e., ~1800×10^{-5} SI). Several intervals have susceptibility much greater than the average value for Hole 1105A and correspond to intervals with a higher abundance of magnetite in oxide or oxide-bearing (olivine) gabbro.

Thermal conductivity was measured on 28 gabbro pieces taken at irregularly spaced intervals along Hole 1105A. Measured values range from 1.804 to 2.981 W/(m·K), with an average of 2.16 W/(m·K). This limited dataset from the shallow portion of the section at Atlantis Bank does not show any relation between rock type or alteration and thermal conductivity.

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