March 2, 2005

IODP EXPEDITION 305: OCEAN CORE COMPLEX FORMATION, ATLANTIS MASSIF SITE U1309 SUMMARY

Hole U1309D: Latitude: 30° 10.1195' N, Longitude: 42° 07.1131' W, 1645 mbsl

SCIENCE SUMMARY

Site U1309 (Prospectus Site AMFW-01A) is located on the central dome of Atlantis Massif, 15 km west of the median valley axis of the Mid-Atlantic Ridge, where the seafloor coincides with a corrugated detachment fault surface. Site U1309 comprises eight holes drilled within 2 km of one another and along a spreading-parallel corridor (see Expedition 304 Site U1309 Site Summary). Hole U1309D penetrates a dominantly gabbroic crustal section, providing core that documents the interplay between magmatism, deformation, and alteration prior to, during, and subsequent to, a period of footwall displacement and denudation associated with detachment faulting.

Drilling in Hole U1309D took place over two periods for a total of 15 days during Expedition 304; penetration reached 401.3 mbsf, with an average recovery of 64%. During Expedition 305, Hole U1309D was deepened to 1415.5 mbsf. The total average recovery is 74.8%.

A total of 1529 shipboard samples have been taken during Expedition 305 for making thin sections (415), and for discrete sample measurements (ICP-MS, 145; magnetic properties, 321; physical properties, 392; X-ray diffraction, 256). 274 half-core pieces were measured for thermal conductivity. 15 samples of gabbro, olivine-bearing gabbro, olivine gabbro, troctolite, and dunitic troctolite were taken at regular intervals from ~400-1400mbsf in Hole U1309D for microbiological investigations.

Igneous rocks recovered from Hole U1309D record a series of intrusions that have occurred within the sub-axial zone of the spreading center. Mafic rocks recovered in Hole U1309D during Expeditions 304 and 305 fall into six major rock types : basalt and diabase (~3%), oxide gabbros (~7%), gabbroic rocks (~56%), including gabbros, gabbronorites, olivine-bearing gabbros, disseminated oxide gabbros, and microgabbros, olivine gabbros and troctolitic gabbros (~25%), and troctolites (~3%). Ultramafic rocks are, in general terms, dunitic troctolites (~5%), and peridotites (<1%). Dunitic troctolites are all olivine-rich troctolitic rocks, including wehrlitic troctolites. The gabbroic rocks have compositions that are among the most primitive sampled along the Mid-Atlantic Ridge, as reflected in Mg numbers ranging from ~67 to 90, and low $Ti0_2$, Na_20, and trace element contents. All diabases have basaltic compositions, overlapping those of the glasses from the mid-Atlantic ridge. Almost all gabbroic lithologies are crosscut by veins/dikes of variable thickness and composition, including gabbro, oxide-bearing gabbro and trondhjemite. Most ultramafic and olivine-rich troctolitic rocks have undergone some extent of hydrothermal alteration. Some intervals are very fresh (locally less than 1 or 2% serpentinization), and unique in the ocean drilling records.

Olivine-rich rocks with low modal plagioclase and clinopyroxene were characterized as “dunitic troctolites” to avoid genetic implications, but to recognize the distinctive textures (rounded olivines, interstitial plagioclase and/or clinopyroxene) and modal composition of these rocks. They could represent the ultramafic primitive endmembers of the recovered igneous section. Their origin will be further addressed by detailed post-cruise studies. The occurrence of such rocks is rare at mid-ocean ridges; In Hole U1309D their abundance reaches > 5%, with the thickest units between 1092 mbsf and 1236 mbsf.

The most important lithologic type recovered is the gabbro group. It has a wide range of grain size variability, from microgabbro to pegmatite, and modal compositions, commonly including minor quantities (rarely exceeding 10%) of olivine, Ti-oxides, and/or orthopyroxene. Olivine gabbro is the second most common lithology in the cores from Hole U1309D, with an olivine mode that nearly always exceeds 20 %. The modal composition of this rock type is highly variable on a sub-meter scale. Troctolite is spatially associated with olivine and troctolitic gabbro. The texture of troctolite is irregularly seriate, locally with poikilitic clinopyroxene.

Oxide gabbro, defined by the occurrence of more than 2% modal Ti-oxide minerals, is also an ubiquitous lithology (about 8% of the rocks recovered during Expedition 305). The most common type of Ti-oxide occurrence is of dispersed patches in undeformed, generally coarse-grained gabbro. Oxide gabbro also occurs as discrete dikelets or layers, with either sharp or diffuse boundaries with the surrounding lithology, or are spatially associated with ductile deformation zones. Many oxide gabbros contain apatite and zircon as accessory minerals.

Basalt and diabase are common in, but not restricted to the upper part of the footwall at Site U1309 (Holes U1309B and D). Diabase intrusions were encountered down to ~ 1378 mbsf in Hole U1309D, and are commonly a few meters thick. They are characterized by a fine-grained sparsely phyric to intersertal texture, few phenocrysts and a glassy matrix. They have compositions ranging from tholeiitic basalt to basaltic andesite, overlapping basaltic glasses from the Mid-Atlantic Ridge.

Alteration mineral assemblages record cooling of the plutonic rocks, from magmatic conditions to zeolite facies, during unroofing and uplift of the Atlantis Massif. Overall, the alteration is moderate and tends to generally decrease down core, with the exception of more intense alteration sequences in the intercalated dunitic troctolites, olivine gabbros, and gabbros between ~1090 and ~1230 mbsf, and in the lowermost gabbros and olivine gabbros. The coarser grained gabbro intervals generally appear to be more altered than the medium- to coarse-grained gabbros and olivine gabbros. In dunitic troctolite intervals, alteration is mostly restricted to heterogeneous serpentine networks, with strong alteration gradients from the contact with intensely veined intercalated gabbros to the fresher cores of the dunitic troctolite units. The latter locally contain intervals of very fresh (as low as 1% serpentinization) olivine-rich (up to ~90%) rocks. The alteration is commonly stronger in the vicinity of metamorphic veins. The vein assemblages change with lithology (local control), and with depth, likely reflecting changes in late fluid chemistry. The overall metamorphic history can be divided into a high temperature phase and, by far the most important, a low-temperature phase that mostly reflects alteration at temperatures less than 500°C.

A common manifestation of alteration is the development of corona textures consisting of partial or complete replacement of olivine by talc/tremolite and replacement of the edges of neighboring plagioclase by chlorite. Serpentine is generally present only as relics within fractures in olivine, as a late replacement of olivine cores, or, rarely, as a replacement of tremolite. In a few cases calcite is also found associated with serpentine, talc, tremolite. Dark green amphibole veins are the most common vein type in Hole U1309D (~48%); they are the major contributor to the overall observed alteration. Later, light green amphibole veins, commonly in a slip-fiber configuration, invariably crosscut the dark-green veins. They contain mostly tremolite and/or actinolite, and, in more olivine-rich lithologies, talc and/or serpentine. These veins are commonly associated with up to several cm wide alteration halos, especially in olivine-rich rocks, containing talc and/or tremolite, amphibole, chlorite, albite, prehnite, zeolite, or hydrogarnet. The latest stages of alteration involve emplacement of a variety of veins, postdating the greenschist facies alteration, and containing variable mineralogy that, at least in part, correlates with depth. They can contain quartz, carbonate, zeolite, prehnite, and anhydrite. Overprinted on all of these is a late, low-temperature set of clay-rich (probably saponite) veins.

The overall trends in alteration and the changes in secondary mineralogy suggest that there may be two separate secondary processes that have affected the footwall in the vicinity of Hole U1309D. In the upper ~840 m, seawater/rock interaction may pervade the sequences. Below that depth, the nature of and the fluctuations in degree and style of metamorphism are related to fluids of a different composition percolating along fault zones and zones of deformation. Hence, the rocks record an extensive history of gabbroic rock/fluid interaction, possibly including magmatic fluids.

Crystal-plastic, magmatic, and brittle deformation identified in material cored during Expedition 305 show a low overall degree of deformation. The temporal evolution of the deformation history in Core U1309D may be summarized as follows:
1) About 22% of all recovered rocks show a generally weak magmatic foliation attributed to processes related to igneous emplacement of the gabbro bodies. The growth of clinopyroxene megacrysts, commonly poikilitic, appears late in the crystallization sequence of the gabbros.
2) Microstructural observations commonly indicate a weak to moderate, high-temperature crystal-plastic strain overprint of the magmatic textures, which is generally difficult to recognize in hand samples.
3) Clearly overprinting the high temperature plastic fabric when present, and much more localized are a series of discrete, relatively thin (generally a few cm), lower temperature and/or higher strain rate, porphyroclastic and mylonitic shear zones. These shear zones are commonly, but not systematically, closely spatially associated with oxide concentrations. Overall, crystal-plastic foliation has been identified in less than 3% of the core.
4) Magmatic veins seem to be the expression of late, leucocratic magmatic intrusions, and they do not show any associated high-temperature deformation.
5) Serpentinization occurs along microcracks and veins, and appears in any olivine-bearing rock. It is more prominent, although highly heterogeneous, in olivine-rich lithologies.
6) All fault and late, silica-rich hydrothermal veining occurs in the greenschist facies or at lower grades. Crosscutting relationships indicate a complex succession of events during fluid flow and deformation. The amount of strain recorded by cataclastic features is negligible overall, except for four fault zones (at ~ 695, 756, 785, and 1107 mbsf) identified by fault gouge occurrences. These faults, however, are relatively thin, unlikely to have accommodated large displacement, and more likely reflect late deformation internal to the overall gabbroic massif, rather than major, regional tectonic event(s). The relative timing of serpentinization (5) and late brittle events (6) is not clear. They probably represent distinct events based on the difference in fluid chemistry required for serpentinization versus the formation of talc- and tremolite-rich veins.
7) Open fractures. Late fracturing of the rock results in fractures that are open and have no apparent offset. Sulfides occur along these fractures only in the lower part of the drilled section (>600 mbsf).

Onboard physical property data in combination with downhole logging data provide an initial means to assess which aspects of the geological characteristics of the modal core of Atlantis Massif might give rise to the broader scale geophysical signals. In addition, inherent rock properties such as magnetic susceptibility and thermal conductivity can be assessed and related to lithology and alteration.

Magnetic susceptibility is highest for the dunitic troctolites recovered from Hole U1309D and it is quite low for most of the gabbros. The dunitic troctolites are commonly moderately to highly serpentinized and the susceptibility reflects magnetite produced during the alteration process. Magnetic susceptibility is a reliable indicator of oxide-rich intervals but intervals with disseminated oxide (< 1% estimated modal abundance) did not always have associated susceptibility peaks and, in at least some cases the lack of correlation between oxides and susceptibility increase might be due to the oxide phase being mostly ilmenite instead of magnetite. The natural remanent magnetization (NRM) of the rocks was determined onboard following removal of a drilling-induced overprint. Alternating field (AF) demagnetization (typically 30 mT) was used to remove the overprint and the bulk of the archive half sections show negative inclination direction, which corresponds to a reversed magnetic polarity epoch. Thermal and AF demagnetized discrete samples for the most part show the same reversed magnetic inclination. There are a number of small intervals that have positive NRM inclination. Essentially all correspond to diabase, troctolite, and dunitic troctolite, all of them being high magnetic susceptibility and intensity rocks. Our working hypothesis is that the change in magnetic polarity reflects the relative chronology between the gabbro crystallization (negative polarity), and the serpentinization and diabase intrusions (positive polarity).

The ~1.4 km sequence of dominantly gabbroic rocks is inconsistent with the prediction that the footwall of Atlantis Massif is an uplifted mantle section where serpentinization is responsible for lower densities/seismic velocities in the upper few hundred meters. A more complex model than was put forward before Expeditions 304/305 will be required. The fact that we did not encounter fresh mantle predicted to be below ~ 1km can be explained in a number of ways, none of which can be ruled out at this point. All require notable geologic variability within the footwall, as supported by significant vertical variability in lithology, alteration and, to a lesser extent, local deformation, documented in the core from Hole U1309D. Lateral variability in footwall structure is also indicated by the occurrence of outcrops of serpentinized peridotite around the Lost City hydrothermal vent field, ~5 km to the South, and by the high seismic velocities at ~800 mbsf indicated by the NOBEL seismic refraction lines, less than 1 km to the North.

A significant change in several core sample and downhole log properties occurs between 280 and 400 mbsf. Density values have reduced scatter and slightly higher average values below 350 mbsf, increasing from 2.8 g/cm^3 in the interval 280-340 mbsf to 2. 9 g/cm^3 in the interval 350-400 mbsf. Average compressional velocity (Vp) of minicores samples in the 280-340 mbsf interval drops to 5.3 km/s (from 5.5 km/s in the overlying 200 m) before increasing to 5.7 km/s at 340-400 mbsf. Logged Vp increases from about 5.5 to 6.0 km/s between 340 and 370 mbsf. Electrical resistivity measured by the Dual Latero log shows a marked increase over the same interval. The low values of all these physical properties are associated with the serpentinization of olivine-rich lithologies (dunitic troctolites and to a lesser extent olivine gabbros that overly them) in the 280-340 mbsf interval.

This change in physical properties from 280 to 400 mbsf indicates an impedance contrast that corresponds to seismic reflectivity. At Hole U1309D it is probably the change from less altered gabbro to more altered olivine-rich rocks that dominates the local acoustic impedance. This is in direct contrast to one earlier interpretation of the main seismic reflector as the base of a regional alteration front. If ~340 mbsf coincides with the D reflector, the average velocity of the overlying section would need to be ~5.44 km/s locally, slightly lower than the 5.54 km/sec value determined by a Vertical Seismic Profile shot to

345 mbsf during the expedition. Both locally and on a broader scale the influence of crack closure with depth may also contribute to the impedance contrasts 300-400 mbsf.

The structural and metamorphic history recorded in the core from Hole U1309D is essentially separated into a high-temperature and a low-temperature event, with no significant deformation occurring under amphibolite facies conditions. Neither the high- nor the low-temperature deformation structures are geometrically consistent with spreading-parallel displacement on the exposed corrugated detachment and its associated deformation. The latter is probably essentially brittle, and highly localized to the upper 100 or 200 meters of the section in Site U1309. In addition, the shipboard paleomagnetic measurements show no significant net rotation (≤15°) of the recorded field with respect to the expected geomagnetic field for this site. This probably precludes a rolling hinge model for the uplift of the core of the Atlantis Massif along a single, concave, normal fault. Instead, a multiple fault system is probably required. The low-angle detachment fault capping the Atlantis Massif must have captured the recovered gabbroic pluton at relatively shallow depth, and transferred it to its present-day position without significant tectonic rotation.

OPERATIONS SUMMARY

Hole U1309D

Operations at Hole U1309D for Expedition 305 began with arrival on site at 1600 hr on 16 January. A water sample was collected from the bottom of the hole and approximately three meters of fill was removed before we initiated coring. Between 17 January and 1015 hr, 23 February, we cored without significant incident from 401.3 to 1415.5 mbsf. Bits were replaced after accumulating nominally 50 hr of rotation time. 20-barrel mud sweeps were circulated every 10 m of advance to clean to hole. At the end of each bit run, the bits returned worn but essentially undamaged, and no significant difference in performance was apparent between the two styles (C-7 and C-9, five runs each) of bit deployed.

Two logging programs were undertaken during the expedition. One program was completed midcruise, sampling the interval from ~835 mbsf to ~170 mbsf. This operation included six logging runs (Triple-combo, FMS-sonic, VSP, UBI, GBM, and wireline heave compensation testing). Our second logging operation followed the conclusion of coring operations, and consisted of two logging runs (Triple combo and FMS). Additional logging operations were foreshortened by tool failure and excessive heave due to weather.

During our midcruise logging run a temperature of ~60°C was measured with the borehole magnetometer. Several attempts were made to verify borehole temperatures prior to initiation of our final logging program. During these attempts (with the WSTP, ADARA temperature shoe, and heat sensitive adhesive strips) we concluded borehole temperatures did not likely exceed the operation limit of logging tools (potentially ~100°C near the bottom of the hole). An additional water sample was also collected during the WSTP deployment.