January 7, 2005

IODP EXPEDITION 304:
OCEAN CORE COMPLEX FORMATION, ATLANTIS MASSIF
SITE U1309 SUMMARY

Hole U1309A: Latitude: 30° 10.1081' N, Longitude: 42° 07.1101' W, 1643 mbsl
Hole U1309B: Latitude: 30° 10.1081' N, Longitude: 42° 07.1101' W, 1643 mbsl
Hole U1309C: Latitude: 30° 10.1081' N, Longitude: 42° 07.1209' W, 1638 mbsl
Hole U1309D: Latitude: 30° 10.1195' N, Longitude: 42° 07.1131' W, 1645 mbsl
Hole U1309E: Latitude: 30° 10.1207' N, Longitude: 42° 07.1057' W, 1644 mbsl
Hole U1309F: Latitude: 30° 10.1999' N, Longitude: 42° 07.2518' W, 1644 mbsl
Hole U1309G: Latitude: 30° 10.5379' N, Longitude: 42° 06.3179' W, 1873 mbsl
Hole U1309H: Latitude: 30° 10.5379' N, Longitude: 42° 06.3179' W, 1873 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 gently sloping, corrugated detachment fault surface. Two drill holes at this site (Holes U1309B and U1309D) penetrate a multiply-intruded and faulted crustal section, providing core that documents the interplay between magmatism and deformation prior to, during, and subsequent to, a period of footwall displacement and denudation associated with detachment faulting. Five shallow penetration holes (Holes U1309A, U1309E-H) were designed to sample the sedimentary carapace and upper few meters of the basement, to test the hypothesis that the upper surface coincides with the detachment fault, and to help constrain the temporal history of denudation.

Site U1309 comprises eight holes drilled within 2 km of one another and along a spreading-parallel corridor. The first five holes, Holes U1309A-E, are located within 30 m of each other, in an area with 2-4 meters of unconsolidated sedimentary deposits above basement. Before initiating coring, we obtained a temperature measurement and seawater sample for microbiology and geochemistry. Bottom water at this site has a temperature of 5.33± 0.6°C, pH of 7.73, alkalinity of 2.16 mM, and salinity of 35.5 g/Kg. A push core at Hole U1309A recovered ~2.5 meters of unlithified tacky mud, above bedrock. This microfossil ooze (with foraminifera and pteropods) includes mineral grains (fresh olivine, and pyroxene), as well as fish remains.

In an effort to assess drilling conditions and begin geologic characterization of the expected detachment fault zone, a single-bit pilot hole was drilled at Site U1309. Hole U1309B was cored to 101.8 mbsf. Recovery was good (overall average 46%), increasing significantly (to an average of 52% for 30-100 mbsf) below the upper, very slow-drilling 25 m. An attempt to set casing for the hard rock reentry system at Hole U1309C was not successful. The casing attempt was abandoned with ~25 m of 13 3/8 in casing pipe standing above the seafloor; it is 20 m east of Hole U1309B and about 30 m southwest of Hole U1309D.

Drilling in Hole U1309D took place over two periods for a total of 15 days during Expedition 304; penetration reached 401.3 mbsf. Despite rough sea conditions that were experienced during some of the drilling, recovery rates were very good - 64% overall. The section from 108 to 126 mbsf (Cores U1309D-18R to -21R) had very low recovery, including one empty core barrel, and a second with only 14% recovery. Logging data suggests this low recovery zone may coincide with a fault zone. Aside from the low recovery interval and the upper 30

m, recovery rates averaged 68%. As drilling conditions in the pilot hole (Hole U1309B) were very good, casing below 20 m in Hole U1309D was deemed unnecessary.

The motivation for this series of shallow penetration holes is two-fold: to check for possible fossils or isotopic signature in the sedimentary deposits to constrain the exposure age of the hypothesized detachment fault, and second, to attempt recovery of possible fault rock at the top of the domal surface. The first shallow penetration core was obtained at Hole U1309A, briefly described above. Overcoring in the top interval of the deep penetration holes (Holes U1309B and U1309D) precluded meaningful recovery from the sedimentary deposits and several meters of basement immediately below. Hole U1309E was offset 10 m east of Hole U1309D in an attempt to recover the sediment and upper meter of basement using the RCB. Disrupted sediments were obtained, as were several fragments of metabasalt. The second attempt at shallow penetration was made about 280 m to the NW of Hole U1309D. Despite clear indications from drilling parameters that we drilled over a meter into hard rock, recovery included only disrupted sediment and a few fragments of metabasalt. No chips of lithified carbonate were recognized. A third shallow penetration hole is located 1.6 km northeast of Hole U1309D, in an area characterized by a broad carbonate cap above basement. This hole was spud into stepped and platy, lithified carbonate sediment. Coring to 3.5 meters using an XCB bit recovered 0.91 m of microfossil ooze, with 3 thin (2-3 cm) interlayers of basaltic hyaloclastite. Glass from the hyaloclastite is oxidized palagonite. No lithified carbonate or intact basement rock was recovered. The sequence of fossiliferous ooze, hyaloclastite, and a clayey material with rounded, largely metabasalt clasts, may provide useful post-exposure data. The latter could be a sedimentary conglomerate but we cannot rule out significant reworking due to drilling in this lowermost interval. Our last shallow penetration core, using the RCB at the same location as Hole U1309G, penetrated to 4 mbsf; recovery includes pieces of basalt, talc-tremolite schist, and one piece of diabase cataclasite. Despite the small return, these samples are significant. Fracture intensity in the diabase is minor, suggesting fairly low strain, but consistent with the sample being part of a process zone associated with a fault system. Although these samples are minimal, they provide the first direct evidence that the corrugated central dome of Atlantis Massif is an exposed detachment.

Twelve samples representing all major rock types recovered were sampled for microbiological investigations from Holes U1309B and U1309D. Onboard cultivation studies indicate growth of matter from two altered gabbro samples at elevated temperature, based on positive fluorescence test. Onshore analyses are required confirm that this is a microbial signature as opposed to being due to inorganic material.

Igneous rocks recovered from Holes U1309B and U1309D on the central dome of Atlantis Massif record a series of intrusions, likely to have occurred at different depths within the subaxial zone of the spreading center and, perhaps, into young lithosphere as it was incorporated in the western flank of the rift axis. Mafic rocks recovered at Site U1309 fall into six major rock types: basalt and diabase, gabbroic rocks including oxide gabbro, gabbro, olivine and troctolitic gabbro, and troctolite. Ultramafic rocks recovered at Site U1309 are, in general terms, serpentinized peridotite, their composition ranging from residual mantle harzburgite and dunite, to cumulate dunite, wehrlite, lherzolite and olivine-rich troctolite. All ultramafic rocks have undergone hydrothermal alteration, and are multiply intruded by later gabbro dikes and/or veins. In the upper 100 m cored interval in both Holes U1309B and U1309D, gabbroic rocks make up 50-60% of the recovered section, basalt and diabase 40-50%, and serpentinized peridotite ~0.5-3% total.

Basalt and diabase are restricted to the upper part of the footwall at Site U1309. Their intrusive contacts, taken with the relative intensity of alteration and veining suggest that

the diabase bodies were emplaced late in the intrusive history of the footwall at Site U1309. Subhorizontal magmatic foliation, taken with paleomagnetic and logging data, suggest that diabase in Holes U1309D and U1309B comprise groups of subhorizontal sheets or sills. The basalt and diabase from Site U1309 are tholeiitic basalts to basaltic andesite, with compositions that overlap basaltic glasses from the entire Mid-Atlantic Ridge.

Gabbroic rocks recovered at Site U1309 are grouped into ten zones based on olivine content, and the proportion of intercumulus phases present. Within each zone, one rock type is dominant, although others are commonly present as magmatic and/or intrusive layers ranging from a few centimeters to many tens of centimeters in thickness. Rock types in each sequence can vary from gabbro, olivine gabbro and troctolite, to oxide gabbro. Grain sizes vary from fine to very coarse and locally pegmatitic. The thickness of each zone varies from ten to many tens of meters. This gabbroic section (300+ meters thick) is cut by numerous, thin, late-magmatic leucocratic dikes, representing a late episode of intrusion of fractionated magma.

The gabbroic rocks from Site U1309 have compositions that are among the most primitive sampled along the Mid-Atlantic Ridge, as reflected in Mg numbers ranging from 74 to 90, and low TiO_2, Na_20, and trace element contents. Most of the compositional variation observed in Site U1309 gabbroic rocks are consistent with a simple mass balance involving increases in the proportion of clinopyroxene with oxides (or olivine in troctolite) that correspond to plagioclase decreases. Site U1309 gabbroic rocks are therefore interpreted as cumulates, which are related to the basalt and diabase, through crystal fractionation processes, to a common parental magma.

Ultramafic rocks recovered at Site U1309 are of two types: those that clearly formed by cumulate igneous processes and are part of the gabbroic section discussed above, and those that lack cumulate textures. The latter have characteristics that suggest a residual mantle origin, but these sections are too serpentinized for this conclusion to be certain based on shipboard observations; onshore analysis can provide the answer.

Alteration mineral assemblages in rocks from Site U1309 record cooling of mafic plutonic rocks from magmatic conditions (>1000°C) to the temperatures of zeolite facies (<100°C) during unroofing and denudation of Atlantis Massif. Many samples from the site, particularly those collected from below 350 mbsf in Hole U1309D display only slight alteration. Individual samples generally display a range of superposed metamorphic conditions, but no single sample records the entire cooling history of the site. The mineral assemblages encountered in any sample depend on what point in its cooling history the rock underwent deformation and/or hydration. The most extensive metamorphic event recorded at Site U1309 is hydration that occurred at and below greenschist facies. Three distinct processes that occurred at temperatures less than 500°C dominated this hydration. Static hydration at 400-450°C formed characteristic tremolite-chlorite-talc corona textures along olivine-plagioclase interfaces and resulted in the formation of tremolite/actinolite from pyroxene in both gabbro and diabase. Plagioclase was stable except in the presence of olivine. The intensity of this hydration decreases with depth, and is localized in and around small gabbroic dikes below about 350 mbsf. In another stage, localized fluid flow led to intense alteration associated with breccia zones above 60 mbsf, and with late magmatic leucocratic dikes below about 160 mbsf. This alteration characteristically produced secondary plagioclase in addition to actinolite and below 370 mbsf, epidote. This alteration episode occurred under conditions similar to the static alteration but generally appears to postdate it. In ultramafic rocks this alteration produced talc-tremolite veins. Finally, in rocks where the coronitic reaction did not go to completion, fracture-controlled serpentinization of olivine is accompanied by replacement of plagioclase by prehnite and hydrogrossular at <350°C.

This assemblage is rare above 300 mbsf, and apparently did not occur in rocks that are now above 130 mbsf, because either olivine or plagioclase was completely removed by the corona-forming reaction.

Within the context of deformation expected in the footwall to a detachment fault at an oceanic core complex, structural observations for Site U1309 show a somewhat surprising lack of deformation immediately below the hypothesized detachment fault exposed at the seafloor. Based on observations in Hole U1309D, five structural units are identified. The boundaries between each coincide with a several of the boundaries between gabbroic zones defined by igneous relationships, with intervals of relatively high cataclastic deformation intensity, and with the location of faults identified in the logging data. The structural boundaries are located in Hole U1309D at 135, 160, 260 and 285 mbsf, and are coincident with thin intervals of ultramafic rock. Based on a combination of observations, we suggest that these thin screens of ultramafic rock acted as zones of weakness during alteration, and may have controlled the late denudation history of Atlantis Massif. The early history of deformation recorded at Site U1309 is constrained by magmatic and crystal plastic deformation fabrics in ultramafic and gabbroic rocks.

Crystal plastic deformation is localized into narrow shear zones (up to 30 cm thick) in both Hole U1309B and U1309D, with no significant change in style or distribution with depth. Crystal plastic deformation is clearly partitioned into more fractionated gabbroic rock types, but is generally lacking in the 400 m section of the footwall transected in Hole U1309D during Expedition 304. The dip of the majority of crystal plastic shear zones at Site U1309 range from 20-60° toward the west; at various depths subhorizontal dips occur as well. Microstructures indicative of deformation by semibrittle processes at amphibolite grade conditions in some parts of the section suggest small strains; the majority of the recovered core shows evidence of only greenschist grade semibrittle/brittle deformation associated with basaltic intrusion and hydrothermal alteration. In many cases this deformation amounts to no more than a pervasive static alteration; pseudomorphs of igneous texture remain largely unmodified. Alteration veins, fractures, cataclasite and breccia record low-temperature brittle deformation. Tentative reorientation of structures using paleomagnetic and logging data indicate that the majority of veins dip toward the east and several faults strike east-west. These observations indicate that denudation of the upper central dome of Atlantis Massif was dominated by brittle and semibrittle processes associated with magmatic intrusion and extension. However, no structures indicative of high displacement by either ductile or brittle processes have been recovered to date.

Paleomagnetic measurements on samples from Holes U1309B and U1309D show dominantly negative inclinations that represent a reversed polarity remanence. However, there are important downhole fluctuations in inclination. Average inclinations determined for core shallower than 180 mbsf are approximately -45°, similar to the reversed polarity dipole inclination expected for this site. A pronounced reduction in inclination angle is evident in the interval from ~180-260 mbsf, where values are typically shallower than -30°; some rocks in this interval have shallow positive magnetic inclinations. At depths > 260 mbsf, the inclinations again are steeper though the average inclination is approximately 5-10° shallower than in the upper 180 meters of the hole. The reversed polarity magnetization components found at Site U1309, particularly from gabbro, provide a robust estimate of the geomagnetic field at the time the magnetization was attained. The mean inclination of the most reliable samples is -49.4° (+3.4°/-2.1°). Crosscutting relations between steeply dipping basaltic dikes and gently to moderately dipping faults, taken with the paleomagnetic data showing little difference in magnetic inclination (mean from most reliable gabbro samples, -51°) from the expected (-49°), suggests little horizontal axis rotation of the

upper ~180 m at Site U1309, the presumed footwall to the fault system exposed at this location in the central dome.

Thermal demagnetization data show multiple components of remanence in several olivine gabbro and troctolites samples. The reversed magnetization component that characterizes most of the rocks from Site U1309 is overprinted by a normal polarity component with moderate inclination. The highest stability magnetization component in these samples is typically of reversed polarity and is isolated at temperatures above 520°-550°C. A lower stability normal polarity overprint is typically removed over the temperature range of ~350°-520°C. Such overprinting indicates reheating of the rocks, most likely associated with magmatic intrusion. Shipboard analyses show this occurred in several intervals cored at Hole U1309D, more detailed onshore analyses may provide paleomagnetic limits for the timing of such events.

The multi-component remanence signatures potentially contain information on the thermal and tectonic history at Site U1309. The highest stability reversed polarity magnetization is shallower on average than the normal polarity overprint although data scatter is also greater; the two components are not antipodal. The possible difference between the normal and reversed polarity directions may reflect the influence of tectonic tilting of the 180-260 mbsf interval after acquisition of the highest stability reversed polarity magnetization. In contrast, the mean inclination from the uppermost 180 meters of Site U1309 (-48°) is essentially identical to that expected from a geocentric axial dipole (±49°) suggesting that this sequence experienced little tectonic rotation about horizontal axes. These shipboard results raise intriguing questions about the validity of the rolling hinge model for core complex formation.

OPERATIONS SUMMARY

Hole U1309A

Operations began with a subsea camera bottom survey to locate suitable places to drill the pilot hole and to install the Hard Rock Reentry System (HRRS). A water sample and temperature measurement were collected for microbiology and geochemistry. Hole U1309A was a punch core with the RCB coring assembly to capture the surface sediments.

Hole U1309B

Rotary coring commenced in Hole U1309B at 0050 hr on 25 November 2004. Final penetration was 101.8 m with 46.7 m of recovery. All cores in Hole U1309B (Cores U1309B-2R to -20R) except Core U1309B-1R (0.0 to 15.5 mbsf) were recovered in nominally 4.5 m increments (half cores). Penetration at Hole U1309B was terminated when the bit ceased rotation and penetration after 86.25 rotating hr. The hole was displaced with drill (fresh) water for logging. The logging operation consisted of three tool string deployments, one each with the triple combo, FMS-Sonic, and a third run to test the new logging winch heave compensation system. Logging results indicate Hole U1309B is deviated ~ 7° to the northeast. Hole U1309B ended at 0805 hr 1 December 2004.

Hole U1309C

The Hard Rock Reentry System (HRRS) was deployed with three joints of 13.375 in. casing with a designed penetration of 31.6 mbsf. All components were assembled starting at 0805 hours on 1 December, 2004. The vessel was offset ~ 20 m west of Hole U1309B, and Hole U1309C was initiated at 0945 hours 2 December, 2004. Hammer drill operations continued to 1655.0 m (dpm) or 6 mbsf when penetration and rotation effectively stopped. Inspection with the subsea camera showed that the running tool had released from the casing. Hole U1309C ended when the bit cleared the rotary table

at 0755 hours, 3 December 2004. Disassembly of the running tool revealed no detectable reason for the early release.

Hole U1309D

The HRRS was deployed for the second time with two joints of 13.375 in. casing with a designed penetration of approximately 22.45 mbsf, ~20 m north of Hole U1309B. Hammer drilling commenced and at 0630 hr and after penetration of 20.5 m rotation on the drill pipe stalled. A camera inspection indicated the casing running tool had released, but the deployment of the HRRS casing was within operational tolerance. The reentry cone was released, and a subsea camera survey indicated successful deployment of the reentry system. Operations at Hole U1309D continued by opening a hole using the RCB system to 131.0 mbsf. Cores U1309D-1R to -22R were cut with 51% average recovery.

The bit was pulled after a conservative rotating time to ensure an unobstructed borehole would be left for future deepening. The bit cleared the rotary table at 1520 hours on 10 December 2004, suspending operations at Site U1309.

Hole U1309D was deepened to 401.3 mbsf between 22 and 30 December. During pipe trips an obstruction was repeatedly encountered at 48-49 mbsf, but was easily passed with rotation of the bit. Logging was attempted with the XCB/APC assembly (as part of our operation strategy was to attempt shallow cores on top of the dome with the XCB following logging) but the logging tools would not pass the obstruction noted above. After shallow penetration operations, Hole U1309D was reentered with a logging bit and while triple-combo and FMS runs were successful, the UBI run was not attempted since the second FMS pass ended with fallen rock briefly trapping the tool in the hole.

Hole U1309E

Hole U1309E was initiated with the RCB system 10 m east of Hole U1309D. The hole was cored without circulation to a depth of 3.8 mbsf (Core U1309E-1R).

Hole U1309F

Hole U1309F is 275 m NW of Hole U1309D. This location was selected to attempt to core through lithified carbonate and into basement. Hole U1309E was cored to 4.8 mbsf (Core U1309F-1R).

Hole U1309G

The target for Hole U1309G was an area of extensive lithified carbonate identified during a seafloor submersible survey in 2000. With our subsea camera we were able to see a marker deployed at this location during the 2000 submersible survey. Core U1309G-1X penetrated to 3.5 m, recovering just under a meter of sediment and drilling-disturbed hard rock. An APC barrel was deployed to see if we could recover an intact section through the sediment and into basement, but the core barrel parted and no core was recovered.

Hole U1309H

As the final operation on Expedition 304, we attempted to recover the sediment blanket and basement at the same location as Hole U1309G, using the RCB system. The first core barrel returned empty, but a second attempt (Core U1309G-1R) was successful.