**IODP Expedition 399: Building Blocks of Life, Atlantis Massif**

**Site U1601 Summary**

## Background and Objectives

Site U1601 (proposed Site AMDH-2A) is located on a flat region near the southern wall at the top of the Atlantis Massif, at a water depth of 850 m. Mass wasting along the southern edge of the massif has created steep cliffs that expose a 3000 m cross section of the internal structure. The southern wall is predominately composed of variably altered peridotite with intermittent mafic plutonic intrusions.

The location of Site U1601 was chosen in part based on the success of drilling in this region during International Ocean Discovery Program (IODP) Expedition 357. The central Sites M0069A, M0072B, and M0076B were drilled to depths of 12.4–16.4 meters below seafloor (mbsf), with recoveries ranging between 52% and 75%. Recovered cores contained diverse lithologies with upper layers that included calcareous sediment, basalt, and dolerite. Serpentinized harzburgite was recovered in the deeper sections of all three boreholes, and water column concentrations of $H_2$ were elevated to ~40 nM above these locations, suggesting that deeper drilling may encounter rocks undergoing active serpentinization. It was also hoped that a hole at this site would recover a complete section through the detachment fault zone, suggested to be ~100 m thick. Several of the shallow holes of Expedition 357 had recovered fault rocks including cataclasites and talc-tremolite-chlorite schists. Thus, a hole located near one of the central sites could address many of the primary goals of the expedition.

Hole M0069A was specifically targeted as it had some of the best recovery during Expedition 357. It was also the location of the deepest serpentinite sample subjected to microbiological analyses (14.6 mbsf), revealing cell densities of 10–24 cells/$cm^3$. Genes from putative indigenous subsurface organisms were identified from Core M0069A-92R and other nearby drilling locations.

## Operations

### *Port Call and Transit to Site U1601*

IODP Expedition 399 (Building Blocks of Life, Atlantis Massif) began in Ponta Delgada, Portugal, at 0800 h on 12 April 2023 with the *JOIDES Resolution* tied up at Dock 12, NATO Berth. Port call activities were minimal because most of the activities occurred during the tie-up in Tarragona, Spain. All oncoming scientists and JRSO staff boarded the vessel on 13 April. All personnel received a COVID self-test kit the night before to be used before joining the group and boarding the bus to the ship. The COVID-19 Mitigation Protocols Established for Safe JR Operations (COPE) were followed, which included daily antigen tests and mask wearing for all personnel for at least 6 days. Once on board, a general welcome and introductions were conducted, including ship and laboratory safety presentations and tours. One member of the science party disembarked the vessel. At 1400 h on 15 April, after a first lifeboat drill, the voyage to Site U1601 (proposed Site AMDH-02A) began. We arrived at Site U1601 at 0530 h on 19 April, completing the 937 nmi transit from Ponta Delgada with an average speed of 10.7 kt. The ship was in dynamic positioning (DP) mode by 0551 h, starting operations at Site U1601. The COVID mitigation period ended at 1815 h.

*Hole U1601A*

The objective at Site U1601 was to core a 200 m deep hole through the detachment fault at Atlantis Massif. We chose IODP Site M0069 as a reference location, which was drilled in 2015 with the British Geological Survey RockDrill2 during IODP Expedition 357 on the RSS *James Cook*. The operational plan called for a reentry system installation, which required drilling a ~50 m deep pilot hole to assess the formation.

On 19 April, the rig crew assembled a bottom-hole assembly (BHA) with a rotary core barrel (RCB) and C-7 drill bit and deployed it to 854 meters below rig floor (mbrf) near the seafloor. The subsea camera was deployed for a brief seafloor survey. Site M0069 was immediately located thanks to several meters of pipe sticking out of the 2015 hole as well as various skid marks and sampling spots left by the ROV *Jason* in 2018. Our survey line extended 60 m southwest of Site M0069 and showed sand waves along the seafloor, as were also seen more clearly on the 2018 ROV footage. No prohibitive obstructions or hazards were identified. As was true for most deployments of the subsea camera, two Niskin bottles attached to the camera frame were triggered to collect bottom water samples before the frame was retrieved. The seafloor was tagged at 861 mbrf. Operations in the pilot Hole U1601A began by pushing the bit into the sediment with minimal rotation (5 rpm) and minimal pump (5 strokes/min) for 2.4 m. The core barrel for Core U1601A-1R was retrieved at 2045 h and was empty. Core 2R was advanced 9.7 m, and subsequent Cores 3R through 12R, recovered on 20–21 April, advanced 4.8 or 4.9 m each to a total depth of 60.6 mbsf. Recovery ranged from 1% to 72%, with an average of 26%, increasing downhole. At 1245 h on 21 April and at 56.3 mbsf, the bit became stuck. The rig crew tried to free the bit for the remainder of the day, without success. At 0045 h on 22 April the decision was made to deploy the Schlumberger pipe severing tool. The first two severing attempts failed, and the third attempt at 1243 h succeeded in severing the pipe at 10.1 mbsf. The drill string was retrieved, and the end of pipe cleared the rig floor at 1730 h, ending operations at Hole U1601A.

*Hole U1601B*

Assembly of the drill-in casing system began late on 22 April. The upper guide horn was removed to create the space in the moonpool area needed to assemble the ~22 m long 13⅜ inch casing string, hydraulic release tool (HRT), landing platform, and free-fall funnel (FFF). The stinger BHA, including a mud motor, underreamer, and 12¼ inch bit, was assembled and tested. The reentry system was lowered to the seafloor and drilling in Hole U1601B began at 1455 h on 23 April. Sepiolite mud sweeps were pumped every ~4 m. At 1215 h on 24 April, we reached the target depth of 26.0 mbsf. The “go-devil” trigger tool used to release the HRT from the reentry system was dropped and pumped down the drill string with 25 strokes/min until it landed, with a pressure drop indicating that the release had occurred. However, several attempts to pull the stinger subassembly out of the casing subassembly were unsuccessful despite turning the pumps on and off several times to work the underreamer. At 1430 h the decision was made to retrieve the subsea camera, and then the entire reentry assembly back to the rig floor. The rig crew started to disassemble the reentry system, with the stinger bit at the rig floor at 2353 h on 24 April. The mud motor was severely damaged; the lower section of the housing holding the bearing support, a 12 inch long cylindrical piece, had broken off and was missing.

The rig crew needed time to assess the situation, identify an alternative method for deploying a reentry system at Site U1601, and build that system. We decided that while this was happening, we would move to Hole U1309D to conduct the fluid sampling program and, depending on conditions, initialize coring.

*Hole U1601C*

After operating at Site U1309D from 25 April to 1 May, we returned to Site U1601 to deploy a reentry system in a new hole, U1601C. This was a different system from the one we were not able to release in Hole U1601B. It did not have a mud motor, underreamer, or a casing release tool. Instead, the plan was to drill a 14¾ inch, ~22 m deep hole, reenter the hole with a 9⅞ inch coring bit, drop a casing-cone assembly by letting it free-fall into the hole using the drill string as a guide, and begin coring. By 2254 h on 1 May the ship had moved the 2 nmi from Hole U1309D to Hole U1601C in DP mode. Hole U1601C is located 20 m northeast of Hole U1601B.

*Summary of Bit Runs with Coring Results*

The following is a summary of the bit runs in Hole U1601C, with the following information for the coring runs (bit runs with a coring bit): number of hours the bit was cutting core at the bottom of the hole, the cores retrieved, the interval cored in mbsf, and the average recovery.

- Bit run 1, drill casing hole.
- Bit run 2, coring run 1, 50 h, Cores 2R–55R, 23–284.9 mbsf, 60% recovery.
- Bit run 3, coring run 2, 54 h, Cores 56R–132R, 284.9–658.4 mbsf, 84% recovery.
- Bit run 4, coring run 3, 50 h, Cores 133R–197R, 658.4–973.6 mbsf, 74% recovery.
- Bit run 5, coring run 4, 50 h, Cores 198R–240 R, 973.6–1182.2 mbsf, 62% recovery.
- Bit run 6, wireline logging and water sampling.
- Bit run 7, milling.
- Bit run 8, coring run 5, 44 h, Cores 242R–259R, 1182.2–1267.8 mbsf, 63% recovery.

*Bit Run 1: Drill Casing Hole*

At 0130 h on 2 May, assembly of the BHA with a 14¾ inch drilling bit was complete. After reinstalling the upper guide horn once more, deployment of the drill string began at 0315 h, was paused at 0400 h for general rig servicing, and was complete at 0630 h. Drilling the initial 14¾ inch wide and 23 m deep hole progressed slowly but steadily and was complete at 0615 h on 3 May. The drill string was retrieved, with the bit clearing the rig floor at 1025 h.

*Bit Run 2: Install Casing and First Coring Run*

Two joints of 10¾ inch casing, with a 10¾ to 13⅜ inch crossover at the top, were welded together and staged in the moonpool area. An RCB BHA with a new 9⅞ inch C7 bit was made up and deployed through the casing, starting at 1345 h. The subsea camera was launched at 1610 h. As the ship was maneuvered to the Hole U1601C coordinates, we passed Hole U1601B, which had a hole in the center of a cuttings cone. At the Hole U1601C coordinates, 20 m to the northeast, a "pond" of white sepiolite slurry came into sight, but the hole was not visible. After a short period of poking into the "pond," the bit reentered Hole U1601C at 1925 h and reached the bottom of the hole without detecting any fill. The bit was raised 8.7 m and the camera frame was retrieved. The rig crew installed the FFF around the drill string and attached it to the top of the 13⅜ inch casing crossover. At 2334 h, the casing-cone assembly was dropped into the moonpool and down the drill string. At 0005 h on 4 May, the subsea camera was launched to confirm that the reentry assembly had properly landed in the predrilled 23 m deep hole, which was visually confirmed. The camera frame and Niskin samples were retrieved and the first core barrel was dropped. Unusually high pressure was indicated, which could have resulted from plugged jet nozzles. A second barrel was dropped without incident, and coring began. Coring progressed remarkably well, far exceeding expectations by reaching 284.9 mbsf in the first coring run. The subsea camera was launched once more while the drill string was being retrieved to confirm a clean exit of the bit from the reentry cone, confirming that the reentry system installation was fully successful. With the camera near the seafloor, we also briefly navigated over Holes U1601A and U1601B, identified the cutting cones, and confirmed that the seafloor was clear of any artifacts. The drill string was retrieved, clearing the rig floor at 1830 h.

*Coring Runs 2, 3, 4, and 5 (Bit Runs 3, 4, 5, and 8)*

Despite having exceeded the planned penetration of 200 m at this site with the first coring run, the science party decided repeatedly to continue deepening Hole U1601C. Three more coring runs were completed from 8–25 May, followed by bit runs 6 and 7 for wireline logging and water sampling, and milling junk at the bottom of the hole, respectively. A fifth and final coring run with bit run 8 was conducted from 29 May to 2 June.

All 4-stand coring BHAs were equipped with new C7 coring bits. All reentries were successful. ~20–30 m of soft bridges or hole fill were tagged after each reentry and never posed a significant problem to wash down. Down to Core 178R (881.5 mbsf), 30 bbl mud sweeps were pumped every ~10 m of coring. Subsequent sweeps used 20 bbl of mud every ~10 m to conserve mud. Likewise, the final 50 bbl sweep at the end of each run was reduced to 30 bbl below that depth. Mud sweeps were followed with 2×–7× the open hole volume of seawater at the end of each run. The bit used for run 4 (third coring run) returned with 16 tungsten carbide teeth missing, a degree of wear considered acceptable and not traceable to any particular event. The bit used for run 5 had lost the tips of all four roller cones. One of the cones had kicked inward, losing parts of the bearing, including the plug seal. Dozens of tungsten carbide teeth were missing or damaged. This led to the decision to conduct the milling bit run 7.

After bit run 4, we tested the Elevated Temperature Borehole Sensor (ETBS), which malfunctioned on previous deployments and had been repaired in the meantime. The test deployment inside the drill string returned valid temperature data, closely following the temperature profile measured by the Conductivity-Temperature-Depth (CTD) sonde ~6 h later outside the drill string.

After bit run 5, the hole was replaced with freshwater (drill water) (5550 bbl, 4710 strokes) to improve the resistivity contrast during subsequent wireline logging. When the drill string was retrieved to 55.5 mbsf, another 20 bbl of freshwater were pumped to top off the hole.

*Bit Run 6: Wireline Logging and Water Sampling*

We decided to conduct a full suite of wireline logging operations as well as borehole water sampling in Hole U1601C before attempting a final coring run in this hole. The intent of this sequencing was to minimize the various risks of not gathering the logging data for this >1 km deep legacy hole. On 26 May, a 3-stand BHA with a logging bit was assembled, without a floating valve and including a large bore landing saver. The rig was serviced, the drill string was deployed, the subsea camera was launched, and Hole U1601C was reentered for the fifth time at 0406 h. The bit was positioned at 30.9 mbsf and the camera was retrieved.

The first wireline logging tool string was assembled, including the logging equipment head-mud temperature (LEH-MT) for borehole and tool temperature, Hostile Environment Natural Gamma Ray Sonde (HNGS) tool, and the Hostile Environment Litho-Density Sonde (HLDS) for bulk density and photoelectric factor. We also added the IODP ETBS to the bottom of the tool string. The ETBS does not transmit data in real time. Logging started at 0715 h and ended at 1530 h on 26 May. The log-down pass tagged hard at 1077 mbsf (105 m above bottom). During both the log-down and the log-up pass, the tool string was held every 100 m for 10 min for the ETBS to acquire temperature equilibration time series.

The second logging tool string, including the Accelerator Porosity Sonde (APS), the High-Resolution Laterolog Array (HRLA) resistivity tool, and the Ultrasonic Borehole Imager (UBI), started at 1700 h and was completed at 0225 h on 27 May. The tool string tagged at 1071.5 mbsf, slightly shallower than the first run. Logging with the third tool string, including the HNGS and the Magnetic Susceptibility Sonde (MSS), began at 0300 h and ended at 0830 h. This run reached 1075.5 mbsf. For the fourth tool string, including the Versatile Seismic Imager (VSI), we targeted the daylight hours to comply with marine wildlife protection protocols. At 1030 h the protected species watch and preparation of the air guns began. At 1400 h the logging attempt was aborted and postponed due to issues with cabling or software. Instead, we deployed the Formation Microscanner (FMS) and Dipole Shear Sonic Imager (DSI) tool as the fourth logging tool string. This run began at 1445 h and ended at 2350 h with two log-up passes completed. This fourth run reached 1070.0 mbsf. The tools were rigged down at 0045 h on 28 May 2023.

We still had the postponed VSI to run as the fifth and final logging tool string. However, this required daylight, so we proceeded with borehole water sampling objectives instead. The plan was to deploy both Kuster Flow Through Samplers (FTS) in series, with the ETBS at the bottom, using the coring line. We planned to do this three times, for a total of 6 sampling stations down the borehole. The first run started at 0205 h on 28 May and ended at 0340 h. After laying out the tools, removing the water samples, and resetting the tools, the second deployment started at 0515 h and ended at 0725 h. The third deployment started at 0830 h and ended at 1225 h.

The prior issues with the VSI had been resolved and the rig was again readied for wireline logging. The protected species watch began at 1430 h on 28 May and the fifth logging tool string was deployed at 1435 h. An issue with the telemetry head required retrieval of the VSI string at 1515 h and replacement of the telemetry head. The air guns were prepared and at 1640 h the tool string was redeployed to 1069 mbsf. Given the remaining daylight hours, the measurement stations on the log-up pass were set at 100 m intervals. The run was completed at 2105 h.

We decided to conduct a fourth water sampling run because one of the samplers on a previous run only recovered ~5% of the chamber volume, and because the results from the other water samples were encouraging. The dual Kuster FTS and ETBS configuration was deployed once more at 2215 h and was back on deck at 0055 h on 29 May. We retrieved the drill string equipped with the logging bit, which cleared the rig floor at 0335 h. This ended the wireline logging and water sampling bit run 6. The borehole water sampling effort in Hole U1601C yielded a total of 8 samples at 6 targeted depths intervals: 146, 368, 465, 675 mbsf (sampled twice with ~5% and 100% recovery, respectively), 970 mbsf, and 1074–1065 mbsf (repeated at 1065 mbsf to avoid mud sampled at 1074 mbsf).

*Bit Run 7: Milling*

Before the next attempt to deepen Hole U1601C, we needed to clear the hole of metal debris left behind by previous coring runs, particularly the last one leaving behind a cone bearing. A BHA was assembled with two junk baskets and a 9⅝ inch junk mill. The drill string was lowered to the seafloor at 0430 h on 29 May, filling the pipe every 15 stands from the rig. The subsea camera was launched at 0527 h, and Hole U1601C was reentered for the sixth time at 0704 h on 29 May. The bit was lowered further into the hole and a hard tag was encountered at 1074 mbsf. While washing down to bottom at 1182.2 mbsf, hard spots were encountered at 1084, 1094, 1123, and

1145 mbsf. Milling, which included slowing circulation and rotating and lifting the pipe twice per hour, was carried out from 1430 h to 1945 h. The hole cleaning action ended with pumping a 30 bbl mud sweep with 2× the hole volume of seawater. At 1945 h we began retrieving the drill string, with the mill back on the rig floor at 0050 h on 30 May. The junk baskets contained several metal pieces among the rock cuttings, some that were clearly parts of the lost cone bearing.

*Changes to Shipboard Processing on Recognition of Chrysotile*

While completing coring operations in Hole U1601A in late April, core describers identified and reported the presence of chrysotile veins in the recovered serpentinized peridotite cores. Chrysotile (one of three polymorphs of serpentine) has long been recognized as a common alteration mineral in serpentinized mantle rock, but in most cases in low concentrations. Chrysotile is a type of asbestos, and asbestos is an acknowledged health hazard in asbestos mining and asbestos abating jobs, at industrial concentrations. Regulations for exposure to airborne asbestos emphasize the danger of long-term exposure to significant asbestos dust (defined by most regulations as 0.1 fiber/$cm^3$ as an 8 h time-weighted average in a specific microscopic size range).

On Expedition 399, the occurrence of white vein material of >1 mm thickness, in a few cases up to a size where fibers could be seen with the naked eye, led to concerns by the technical support staff handling cores that their health might be at risk. These concerns were communicated to shore management and Texas A&M University Environmental Health and Safety (TAMU EHS) officials. Consequently, throughout May, core handling, including splitting, sampling, imaging, description, etc., became a major challenge. Precautionary procedures for core handling were implemented but continued concerns and slow communications between ship and shore led to stop-and-go core processing that significantly compromised shipboard scientific data analysis.

After a conversation with shore management on 6 May, shipboard processing of cores at various stages was suspended. On 9 May, after a pause of 5 days, splitting of core sections resumed (regarded as the most hazardous procedure) under special safety protocols approved by TAMU EHS, including utilization of special personal protective equipment (PPE). Scientists and operations personnel participated in the splitting to catch up with the backlog and to allow people who remained concerned about exposure not to carry out these tasks. Rapid core description methods were established to manage the confluence of backlog and continued rapid core recovery. By 15 May, core splitting had caught up with core recovery, and rapid core description had caught up with splitting the next day. This allowed us to discuss, both onboard and with shore management, strategies for reestablishing subsampling. It was decided to start describing the working halves rather than the archive halves, so that shipboard samples could be identified each day without excessive core handling and sampled after shrink wrapping but before storage in the hold. On 19 May, subsampling of section halves for shipboard analysis resumed using the special procedures. A limited number of thin section billets of serpentinized peridotite were cut for processing on shore instead of being prepared shipboard. The material of greatest scientific interest, which constituted the vast majority of the core, therefore could not be fully described shipboard.

On 24 May, JRSO management received the detailed review and advice from TAMU EHS and forwarded it to the ship. The document stated "…Though widespread or significant contamination aboard the vessel is unlikely at this time…," and recommended that "If any ongoing assessment of workspaces positively identifies asbestos contamination, associated activities should cease immediately until additional review can determine the likely cause, potential for exposure, and the feasibility of resuming work…" On 25–26 May, over fifty swab samples of laboratory surfaces and floors were collected by JRSO staff and images of putative chrysotile fibers were sent to shore. Since cleaning of many parts of the laboratories had been suspended as a precaution, it is not clear whether these fibers accumulated before or after the precautionary core handling protocols were put in place. This led to the halt of all core handling including splitting, description, and sampling, so that procedures could be reassessed. On 29 May, per instruction from shore, all core splitting and sampling stopped. Starting with Core U1601C-242R, sections cut and sampled for microbiology were capped, measured with the Whole-Round Multisensor Logger (WRMSL) and Natural Gamma Radiation Logger (NGRL), described through the core liners, and then boxed. The protocols were applied to all cores, including those consisting entirely of gabbro. Expedition 399 was shortened by four days to allow professional cleaning of parts of the ship in Ponta Delgada.

## Principal results

### *Igneous Petrology*

The primary igneous and mantle lithologies are summarized here without regard to changes induced by deformation and alteration. Drilling at Site U1601 recovered in situ sections of mantle rocks with subordinate igneous intrusions. Combined, Holes U1601A and U1601C are dominated by serpentinized peridotites, with 56% harzburgite, 9% orthopyroxene-bearing dunite, and 3% dunite. Gabbroic lithologies constitute approximately one third of the total, and have a range of scales, from millimeter-sized veins to bodies tens of meters in size. Diorite, diabase plus basalt, and ultramafic veins are rare (<1% total).

### *Hole U1601A*

Hole U1601A cores are mostly peridotites (harzburgite to dunite) with subordinate basalt, gabbronorite, and diorite. Six lithologic units were defined within the sequence, primarily based on changes in lithology. Subunits were defined in some of these units where mineral modes changed or where veins crosscut a unit.

The uppermost unit is a microcrystalline aphyric basalt with filled vesicles (Subunit IA) and segregation veins (Subunit IB). Below the basalt is a series of peridotites with primary textures severely overprinted by alteration and deformation. The uppermost peridotite unit (Unit II) is a highly altered and weathered harzburgite. The unit below is a dunite (Unit III) with patches and trails of Cr-spinel, some of which may have plagioclase coronas. The dunite is mostly pyroxene-poor (Subunit IIIA), but grades into an interval of orthopyroxene-bearing dunite (Subunit IIIB). The dunite is underlain by two narrow intervals of highly deformed and altered gabbronorite (Unit IV), separated by a single pebble of dunite (Subunit IVB).

The rest of Hole U1601A is dominated by harzburgite. Initially highly altered and weathered (Unit V), it becomes slightly fresher below 27.7 mbsf (Unit VI). Unit VI peridotite has variable proportions of pyroxene and associated variations in texture. Orthopyroxene proportions vary at the scale of a few to tens of centimeters, ranging from 10% to 25%. Locally, orthopyroxene proportions are below 10% and the harzburgite grades into orthopyroxene-bearing dunite (Subunit VID). From Section 10R-1 (49 mbsf), two different orthopyroxene morphologies are present, granular and interstitial, indicative of a multistage petrogenetic history (Subunit VIE). Clinopyroxene is relatively rare (<3%) and mostly confined to the upper 23 m of the unit. The Unit VI harzburgite contains a narrow interval of deformed gabbronorite (Subunit VIB) and is crosscut by a centimeter-wide diorite vein (Subunit VIC).

Hole U1601A was drilled in the general footprint of IODP Expedition 357, and the igneous stratigraphy of this hole is similar to the nearby Expedition 357 Hole M0069A. The aphyric and microcrystalline nature of the basalt recovered at the top of Hole U1601A resembles the diabase found at Hole M0069A. Like Hole M0069A, a series of harzburgite and dunite was recovered below the basalt/diabase, with the dunite containing Cr-spinel. No gabbroic rocks were recovered in Hole M0069A, although narrow (tens of centimeters) metagabbro and oxide gabbro intervals were observed in Holes M0072B and M0076B located within ~600 m of Hole U1601A. Further, in contrast to the three Expedition 357 central sites (Holes M0069A, M0072, M0076) no talc-amphibole-chlorite schists or breccias were recovered in Hole U1601A. Whether this is a genuine geological difference or relates to the low recovery (~8%) during drilling, the shallowest sections of Hole U1601A are uncertain.

*Hole U1601C*

Recovery of cores in Hole U1601C began beneath casing at 23 mbsf and terminated at 1268 mbsf. Unit I of this hole consists of microcrystalline to aphyric basalt. A long, in situ section of mantle rocks with subordinate igneous intrusions is below. Unit II comprises the primary peridotite lithologies. Subunit names for these lithologies are primarily based on the relative proportions of olivine and orthopyroxene, as the recovered mantle lithologies are dominated by clinopyroxene-depleted varieties. Subunit IIA is harzburgite, IIB is orthopyroxene-bearing dunite, and IIC is dunite. Each gabbroic body encountered has a unit name unless nearby intervals have similar magmatic features even if separated by another unit (e.g., an interval of peridotite).

The distribution of the various rock types in the section is uneven. In the top 180 m, dunite is relatively abundant. Gabbroic intrusions are relatively common between ~120 and ~195 mbsf. Between 200 and 640 mbsf, the section is dominated by harzburgite, with rare dunite and gabbro. The proportion of gabbroic rocks gradually increases again from ~640 mbsf, and gabbros are particularly prevalent below ~950 mbsf.

Orthopyroxene varies in abundance, grain size, and grain shape in the peridotites. These variations occur on decimeter to several hundred-meter scale. Orthopyroxene is less abundant at 0–200 mbsf and 800–1200 mbsf and more abundant around 230, 410, and 750 mbsf. Orthopyroxene abundances and grain sizes correlate, with smaller grain sizes (generally 2–5 mm) in orthopyroxene-bearing dunite and larger grain sizes of 5–8 mm in the most orthopyroxene-rich (>25% orthopyroxene) harzburgite. In addition, grain size of orthopyroxene is smaller in dunite than in harzburgite. As was observed in Hole U1601A, both granular and interstitial orthopyroxene grains have been identified. Clinopyroxene is frequently absent and, where present, is generally rare. Cr-spinel is nearly ubiquitous and reaches higher proportions (1%–3%) in some dunitic rocks.

Minor amounts of other ultramafic lithologies were recovered in the upper 600 m of Hole U1601C. These rocks show a range of modal abundances, ranging from websterite and olivine websterite to orthopyroxenite and wehrlite. They are typically found as veins in olivine-rich peridotite hosts.

Gabbroic bodies are found throughout Hole U1601C and are particularly concentrated towards the bottom (>950 mbsf). In total, we have recorded 438 intrusive bodies, comprising 301 units. Most individual gabbroic bodies are millimeter- to centimeter-sized veins, with progressively fewer intrusions in the 10 cm–1 m, 1–10 m, and >10 m categories. By volume (as measured on the section half surface and uncorrected for unit dips), approximately three quarters of the gabbro bodies are >1 m thick, and approximately one quarter are thicker than 10 m.

Lithologically, the gabbroic rocks are dominated by gabbro, with lesser gabbronorite and olivine gabbro. Other gabbroic lithologies (e.g., troctolite, oxide gabbro/gabbronorite) are relatively rare. Gabbro and gabbronorite have a wide range of thicknesses, whereas troctolite is present only as components of larger gabbroic bodies (0.1–10 m). Oxide gabbro and gabbronorite typically occur in centimeter- to decimeter-scale intervals within gabbroic bodies with less abundant oxide. Texturally, the gabbroic rocks in Hole U1601C are dominated by coarse average grain sizes and granular textures.

Contacts between gabbroic rocks (veins aside) and their host peridotites are generally sutured, and gabbroic rocks are commonly separated from the surrounding peridotite by a centimeterscale zone of troctolite or olivine gabbro. Some gabbros have multi-centimeters long clinopyroxene crystals at the contacts with peridotites.

Other minor lithologies in Hole U601C are diorite and diabase. Diorite occurs as minor components in larger gabbroic bodies and is usually composed of plagioclase and hornblende, commonly with oxides. The diorite has textures suggesting that it intruded into and reacted with gabbro after the gabbro was largely or entirely crystallized. Diabase is present as 3 cm to 2.1 m dikes crosscutting gabbros.

*Alteration Petrology*

Variably altered peridotites and gabbroic rocks were recovered from Site U1601. Peridotites include highly serpentinized (>50 vol% of the total rock volume is serpentinite) harzburgite and minor dunite, as well as orthopyroxene-rich harzburgite that is exceptionally fresh (with ~20–50 vol% serpentinization) in some intervals. In serpentinized peridotites, olivine is highly altered to serpentine, magnetite, and traces of sulfides or alloy(s), as well as iowaite after brucite in Hole U1601A. Because of changes in the operational procedures, the presence of iowaite could not be verified in Hole U1601C. Orthopyroxene is partially to completely altered to serpentine in bastite texture, in which talc and/or chlorite can be locally abundant. These observations, while preliminary, suggest that serpentinization did not result in a major loss of Mg, Si, or Fe, and therefore the addition of water during serpentinization likely resulted in a significant volume increase. The presence of magnetite and sulfides and/or alloy(s) in rocks from Site U1601 is indicative of reducing conditions. Fluid inclusions, locally abundant in olivine from Hole U1601A, may contain gaseous methane and molecular hydrogen.

In shallow intervals, magnetite is locally oxidized to reddish-brown iron oxide and iron oxyhydroxide minerals, indicative of less reducing conditions near the seafloor. At greater depths, magnetite seems less altered. Locally, in zones where serpentinized peridotite is juxtaposed with gabbroic lithologies, disseminated sulfide minerals, with unclear genetic relation with magnetite, were observed in mesh.

In addition to variably altered magmatic veins, most serpentinized peridotites are cut by two vein generations: an earlier generation composed of antigorite and/or lizardite and magnetite, and a later generation composed of chrysotile or picrolite, suggesting that several serpentinization events occurred. Cu-Fe-sulfide veins associated with various proportions of carbonate and serpentine occur locally in the proximity of gabbroic rocks and provide evidence for carbon, sulfur, and base metal mobility between mafic and ultramafic rocks.

Gabbroic rocks, including gabbro, gabbronorite, olivine gabbro, troctolite, and oxide gabbro, show a slight (~3%–20%) to moderate (~20%–50%) and locally high (>50%) degree of alteration. Gabbro is more extensively altered in intervals with a high degree of ductile and brittle deformation, high density of hydrothermal veins, and at contacts with serpentinite. The main types of veins include amphibole, chlorite, talc, carbonate, and zeolite. Brown amphibole coexisting with recrystallized clinopyroxene in deformed gabbroic rocks is possibly of magmatic origin. Localized static alteration associated with hydrothermal veining resulted in the replacement of primary minerals by secondary ones, i.e., olivine by amphibole, talc, serpentine, magnetite, clay minerals, and sulfides; pyroxene by amphibole, talc, chlorite and/or clay minerals; and plagioclase by secondary plagioclase, chlorite, prehnite, and zeolite. Fluid inclusions in olivine, possibly containing reduced volatile species, are locally abundant.

The observations of mineral assemblages, microscopic textures and fluid inclusions, and crosscutting relationships of the alteration assemblages and hydrothermal veins indicate that sequential alteration and deformation of rocks at Site U1601 took place at conditions ranging from amphibolite through greenschist to subgreenschist facies.

While these results are preliminary, the inferred alteration conditions have implications for mass transfer between hydrothermal fluid, mafic, and ultramafic rocks, the interplay between alteration and deformation, and the energy landscape of a serpentinite-hosted subseafloor biosphere in the vicinity of the Lost City hydrothermal field.

*Structural Geology*

The structural evolution of the 1.2 km section cored at Site U1601 varies with recovered rock type. Holes U1601A and U1601C show similar structural geology in their overlapping intervals between 0–55 mbsf, both characterized by rare intervals of crystal plastic and brittle deformation. Below 55 mbsf, all structural observations are recorded from Hole U1601C, as summarized below.

Magmatic veins are common throughout Hole U1601C, cutting both harzburgite and older host gabbro, and showing variable dips that steepen with depth. Thicker intervals of gabbro display rare magmatic foliations, with 75% of measured fabrics restricted to more evolved gabbro and gabbronorite. Isotropic grain size layering/domains are common, with modal layering less common. Domain contacts are typically diffuse and irregular in shape.

Mantle fabrics and serpentine foliation hosted in peridotite vary in intensity, with subhorizontal to moderate dips, barring the interval 630–800 mbsf, where steep mantle fabrics and contacts are noted. In most cases, mantle fabrics and serpentine foliation are misoriented with respect to each other.

Crystal plastic deformation is limited in extent above 630 mbsf. Below 630 mbsf, protomylonitic to ultramylonitic crystal plastic deformation is localized in five 25–50 m thick high strain shear zones and one zone of distributed deformation separated by zones of little deformation. Ninety-five percent of crystal-plastic deformation occurs in gabbroic rocks, and is typically concentrated adjacent to gabbro-peridotite contacts with contact-subparallel dips. Macroscopically, undeformed gabbroic rocks commonly display minor dynamic recrystallization of plagioclase. Mylonitic gabbro samples are dominated by dynamic recrystallization of plagioclase and to a lesser extent, pyroxene and amphibole. All five shear zones display reverse sense deformation. Shear zones 1 (630–675 mbsf), 3 (950–975 mbsf), and 5 (1125–1150 mbsf) also show local normal shear sense. Where present, normal sense mylonitic foliation is steeper (>50°) than reverse sense fabrics; steep mylonitic fabrics overprinted by late shallow mylonitic fabrics are infrequently observed. Rare diabase/microgabbro intervals display both pre- and postdeformation relationships with crystal-plastic fabrics, some of which are crystal-plastically deformed; others are crosscutting mylonitic fabrics. Amphibole and chlorite veins cut mylonitic fabrics. Microstructural fabrics, mineral assemblages, and crosscutting relationships suggest mylonitization occurred at granulite through amphibolite facies conditions.

Sparse occurrences of brittle deformation (fracturing, brecciation, and cataclasis) overprint each crystal-plastic shear zone, as well as some intervals within the low strain zones, including the interval 420–580 mbsf, and are commonly associated with hydrothermal veins. Total strain accommodated by brittle deformation is low. Slickenfibers record dominantly reverse sense shear. Brecciated diabase is observed.

Hydrothermal veins are more common between 0–300 mbsf and 400–750 mbsf, with variable dips. Thin white chrysotile veins are a common feature of the serpentinized harzburgite, and typically mimic the orientation of local serpentine foliation. Talc veins observed in gabbroic intervals, particularly at gabbro-peridotite contacts, are commonly sheared, but can both cut mylonitic foliation in gabbro, or be undeformed.

Fault rocks clearly linked to detachment faulting were not recovered at Site U1601, although some fabrics in gabbroic rocks might be connected. In particular, no talc-tremolite-chlorite schists were recovered. Poor recovery in Hole U1601A and casing to ~22 mbsf in Hole U1601C means that unrecovered fault rocks cannot be ruled out in the top 25 m of Site U1601.

*Geochemistry*

Whole rock chemical analyses (major and trace element concentrations, total carbon and hydrogen, inorganic carbon) were performed on 220 samples from Site U1601 for geochemical (hereafter referred to as CHEM samples) and microbiological (hereafter referred to as MBIO samples) studies. At Hole U1601A, seven serpentinized peridotites and one diabase were collected as CHEM samples and seven serpentinized peridotites and one basalt for MBIO studies. At Hole U1601C, 144 serpentinized peridotites and serpentine veins, 44 variously altered gabbroic rocks, and three diabase and crosscutting carbonate veins were sampled as MBIO samples, and 21 gabbroic rocks and 8 serpentinized peridotites were selected as CHEM samples. The 8 CHEM serpentinized peridotite samples will be processed and measured on shore.

MBIO samples have highly variable compositions compared to CHEM samples. This is likely the result of a sampling bias towards collecting material hypothesized to host more abundant microbial biomass including (1) more altered samples with higher prevalence of veins and/or (2) rocks with mixed mafic-ultramafic lithologies.

The composition of the serpentinized peridotite samples overlaps the field of refractory serpentinized peridotites previously collected during Leg 209 at the 15°20 Fracture Zone (also known as Fifteen Twenty Fracture Zone [FTFZ]; Kelemen et al., 2003; Godard et al., 2008). There is evidence of melt/rock interactions in dunite (iron enrichment) and harzburgite (possible refertilization and melt impregnation).

The composition of Site U1601 gabbroic rocks overlaps with the full range of Site U1309 gabbroic rocks. Gabbro recovered from the bottom of Hole U1601C is more evolved than gabbro from Site U1309. Gabbros at the bottom of Hole U1601C are also the least altered mafic plutonic rocks of Sites U1309 and U1601.

The serpentinized peridotites, gabbroic rocks, and other lithologies collected at Site U1601 contain variable amounts of carbon, mostly hosted in Ca-carbonates, in contrast to the low abundance of carbon in rock samples recovered at Site U1309.

Fluids collected from the series of Kuster FTS runs shortly after logging operations were a mixture of the fresh drill water used to flush the hole, seawater, and possibly formation fluids. Eight cores were returned with significant volumes of fluid due to obstructions between the core and the plastic liner. The geochemistry of these samples was similar to the surface seawater used to flush the hole during drilling, with some samples that had slightly higher pH values. Borehole fluids collected with the Kuster FTS contained detectable $H_2$ and $CH_4$ concentrations that increased with depth. Small fluid volumes that were recovered from the core catcher of most cores contained highly variable $H_2$ concentrations that did not increase or decrease with depth.

*Microbiology*

Microbiological investigations at Site U1601 were intended to explore the potential for life in the shallow subsurface of the Atlantis Massif, at a site where serpentinized rocks were expected to be prevalent. Initial observations of cores from Hole U1601A were consistent with this goal. The surprising depth of Hole U1601C provided the unexpected opportunity to document the distribution of life through >1.2 km of the Atlantis Massif, possibly spanning environmental conditions from highly favorable to too extreme for life. Microbiology samples were collected for traditional analyses such as cell counts, cultivation, and DNA sequencing, as well as organic geochemistry analyses intended to document the presence of organic compounds including lipids, organic acids, and amino acids.

A total of eight MBIO whole-round samples were collected from Cores U1601A-2R to 12R. Six of these samples are serpentinized harzburgite, plus one diabase and one serpentinized dunite.

A total of 191 MBIO whole-round samples were collected from 172 different cores from Hole U1601C. These samples were chosen with the goal of assembling a sample collection that is balanced with respect to apparent biological potential and geological representation, while avoiding pieces that are geologically unique. Most samples are serpentinized harzburgite (60%), followed by serpentinized orthopyroxene-bearing dunite (14%), gabbro (12%), and serpentinized dunite (5%).

Perfluorocarbon tracer (PFT) assays were conducted with (1) samples of loose rubble collected during the core shake out, (2) chiseled shavings of the exteriors of MBIO MBIO whole-round samples, and (3) crushed interior zones after the exteriors were removed by chiseling. PFT levels in loose rubble samples were in the range of 1–10 ppb in most samples and reached 10–25 ppb in 20 samples. A few extreme outliers up to 257 ppb were the result of accidental increases in the rate of PFT delivery during drilling. The fairly consistent and high levels of PFT in loose rubble samples confirmed the successful delivery of PFT during drilling. In contrast, PFT was absent or present at only trace levels in nearly all samples of crushed interiors. These results indicate that surface contamination, as measured by PFT, was largely removed from the interior samples.

The 191 MBIO whole-round samples from Hole U1601C were subsampled for up to 16 different microbiological and biogeochemical analyses, including microscopy (synchrotron-based microscopy, scanning electron microscopy, counts of cells and viral-like particles), sorting of single cells, and analyses of DNA, lipids, and organic compounds. A wide range of cultivation experiments were also conducted, including incubations of crushed interiors in filter-sterilized seawater (157 samples), enrichment incubations (88 samples with different temperatures and nutrients), high-pressure incubations (5 samples), and stable isotope tracer experiments (33 samples).

Samples of borehole water from Hole U1601C were collected with the Kuster FTS to characterize the extent, diversity, and activity of microbial communities within Hole U1601C. In addition, small volumes of fluids collected from the core catcher and analyzed for $H_2$ concentrations were also used for microbiological analyses, including single-cell activity and sorting experiments and DNA sequencing

*Petrophysics*

The petrophysical properties of rocks at Site U1601 were characterized through measurements on whole-round cores, including measurements of natural gamma radiation (NGR), magnetic susceptibility (MS), and gamma ray attenuation (GRA) bulk density. Discrete measurements were completed on rock cubes and cuttings of MBIO samples and included wet mass, dry mass, dry volume, and *P*-wave velocity. Bulk density, grain density, and porosity were calculated from the mass and volume measurements. *P*-wave measurements were also completed on archive-half pieces when rock cube samples were not available in Hole U1601C. Additionally, archive section half core pieces >10 cm in length were selected for thermal conductivity measurements.

Downhole temperature logs were completed in Hole U1601C. A total of five wireline logging tool strings were deployed in Hole U1601C. The diameter of the borehole from caliper measurements is quite regular and is close to the bit size (9.73 inch) with a few larger diameter intervals. The hole is deviated a total of 10° from vertical in a northeast direction at the maximum logging depth (~1060 mbsf).

*Density and Porosity*

The bulk density measured on discrete samples of serpentinized peridotites ranges from 2.34 to 2.72 g/cm$^3$, and averages 2.55 ± 0.08 g/cm$^3$. The grain density ranges from 2.52 to 2.97 g/cm$^3$, and averages 2.66 ± 0.05 g/cm$^3$. Bulk density and grain density increase slightly downhole. Bulk density in gabbros ranges from 2.5 to 3.24 g/cm$^3$. The bulk density was measured downhole using the HLDS on logging run 1. The bulk density has a baseline value of ~2.6 g/cm$^3$, which best fits serpentinized peridotites. Inflections with higher bulk density values are indicative of gabbro.

The porosity of serpentinized peridotites ranges from 1.7% to 20.4%, and averages of 7.0% ± 3.7%. The porosity in gabbro has a range of 0.3% to 13.6%, and averages 3.7% ± 3.5%. Porosity in serpentinized peridotites and in gabbros is lower at shallower depths, higher between 200 and 300 mbsf, and then decreases with depth.

*Sonic Velocity*

Sonic velocity on cube samples was measured along the three principal directions *x*, *y*, and *z* in the core reference frame (CRF). The average velocity of serpentinized ultramafic rocks is 4480 m/s, ranges from 3442 m/s (serpentinized harzburgite, Section U1601C-49R-4, 255.2 mbsf) to 5960 m/s (serpentinized dunite, Section U1601C-193R-1, 950.8 mbsf). The average velocity in gabbroic rocks is higher than that in serpentinized ultramafic rocks and is 5906 m/s, ranging from 4187 m/s (gabbronorite, Section U1601C-52R-2, 267.0 mbsf) to 6532 m/s (olivine gabbro, Section U1601C-32R-2, 170.3 mbsf). The apparent anisotropy of sonic velocity ranges from 0.5% (gabbro; Interval U1601C-22R-1, 56.5–58.5 cm, 120.6 mbsf) to 11.8% (serpentinized harzburgite, Interval U1601C-148R-3, 113–115 cm, 734.9 mbsf). Sonic velocity was measured downhole using the DSI tool on logging run 4. A baseline of *P*-wave velocity of ~4000 m/s and a baseline *S*-wave value of ~2000 m/s are reflective of the high proportion of serpentinized peridotites in Hole U1601C. Velocity overall increases with depth.

The VSI was deployed on logging run 5. A total of 13 stations spaced 100 m apart were measured. *P*-wave velocity measured using the VSI matches the velocities from the DSI. The average velocity across all stations is ~4500 m/s with a range of 3638 m/s at the shallowest depth (~58 mbsf) to 5299 m/s in the deepest part of the hole (~1070 mbsf). This is broadly comparable with existing seismic data.

*Magnetic Susceptibility*

MS measured on the cores ranges from 1,000 to 15,500 instrument units (IU) in serpentinized peridotites. Gabbros have MS values that range from 0 to 23,500 IU. The vast majority of gabbros have very low to zero MS values (<100 IU). The main exceptions are Fe-Ti oxide gabbros that have the highest values of any rock type. MS was measured downhole with the MSS on logging run 3. MS values are variable downhole, with the highest value matching the higher MS measured in serpentinized peridotite cores. Downhole variations in MS measured on cores and downhole match well.

*Natural Gamma Radiation (NGR)*

NGR is low overall with both gabbros and serpentinized peridotites having values of <1 counts/s. The highest values of 3–13 counts/s occur in serpentinized peridotites. NGR was measured downhole using the HNGS on logging runs 1, 3, and 4. Downhole values are low below ~185 mbsf, with a baseline value of ~0.5 gAPI. Between 30 mbsf (right below the logging bit) and ~185 mbsf, values are variable and as high as 35 gAPI. Standard spectral analysis by the commercial software yielded <0.1 wt% $^{40}$K, ~2 ppm $^{238}$U, and ~0.6 ppm $^{232}$Th, with some negative values indicating that the lower counts are below the threshold required to compute accurate K, U and Th concentrations.

*Electrical Resistivity*

Electrical resistivity was measured using the HRLA on run 2 and returned a baseline value of ~3.7 Ωm for the deep penetration. Gabbro is in general more resistive than serpentinized peridotite.

*Borehole Imaging*

The UBI was employed on logging run 2, and the FMS during logging run 4. The FMS logs are of good quality and cover the depth interval 72–1072 mbsf. Serpentinized peridotites have a mottled appearance, likely reflecting the different resistivities of phases present. Gabbros have a more consistent resistivity response. At least four distinct planar features can be identified including conductive planes (darker color, likely fractures), resistive planes (light color, likely veins), and contacts (different textures), and fabrics.

*Thermal Conductivity*

Thermal conductivity was measured on 48 archive section half samples selected from representative lithologies of Hole U1601C. Thirty-eight ultramafic samples were measured with thermal conductivity values ranging from 2.20 to 3.56 W/(m·K) and a mean of 3.02 ± 0.26 W/(m·K). Ultramafic samples from Hole U1601 generally show higher thermal conductivity compared to those recovered from Hole U1601A (averaging 3.02 W/[m·K] and 2.56 W/[m·K], respectively). Twenty gabbroic samples have generally lower thermal conductivity than the ultramafic samples, averaging 2.63 ± 0.54 W/(m·K), and contain much higher variability, ranging from 2.04 to 4.09 W/(m·K).

*Downhole Temperature Logging*

Borehole fluid temperatures were measured several times in Hole U1601C. Five runs of the ETBS were conducted. Maximum temperatures recorded at the bottom of the borehole change over time, as fluids were warmed by the surrounding formation. Logging run 1 reached the bottom of the borehole (997.6 mbsf) ~17 h after flushing the hole with cool freshwater had ceased and recorded a maximum temperature of 70.3°C. Logging run 4 measured a maximum temperature of 88.6°C at similar depths (1009 mbsf), ~64 h after flushing. Logging run 5 recorded a maximum fluid temperature of 91.3°C at the bottom of the borehole (1060 mbsf), ~78 h after flushing.

*Paleomagnetism*

Remanence measurements were made on archive section halves from Holes U1601A and U1601C. These measurements generated 2,967 and 168,296 data points for Holes U1601A and U1601C demagnetization datasets, respectively, which helped determine the NRM of the rocks. Although the greater parts of the holes had NRM inclination values that generally clustered around an expected reversed geomagnetic polarity direction, the inclination values were quite variable. For Hole U1601A, the mean NRM inclination is -22.2° ± 13.5°, whereas for Hole U1601C the NRM inclination is -26.7° ± 32.8°. A low-coercivity drilling-induced component was removed by alternating field (AF) demagnetization steps of 10–15 mT, shifting the distribution closer to the expected geocentric axial dipole (GAD) value of -49°. However, stronger AF steps (>40°) shift the inclination distribution towards the present-day polarity, which suggests that the rocks contain multiple component directions, thus capturing a complex remanence history. The timing of these remanence inducing events (e.g., tectonic rotation, hydrothermal synthesis of magnetite) cannot be uniquely determined from these data and will require further synthesis of geological data.

Archive section half data were complemented by discrete sample measurements. Both paleomagnetic and physical properties cube samples were analyzed using AF demagnetization, thermal demagnetization, isothermal remanent magnetization (IRM) acquisition, and IRM backfield methods. Additionally, paleomagnetism cube samples were pretreated with liquid nitrogen dunking as a way of reducing the drilling overprint. Analysis of these data supported the variable nature in magnetic properties. The numerous high-quality discrete samples measured corroborate the variable inclination and intensity values of the archive section half dataset. Although the bulk remanence of these rocks was carried by magnetite, some samples showed a significant magnetic contribution from gyro remanent minerals, likely some species of iron sulfide. Magnetite populations vary in terms of coercivity, likely indicating variable grain size and oxidation downhole for each hole.

Anisotropy of magnetic susceptibility (AMS) data were predominantly characterized by oblate magnetic fabrics. The relatively low recovery of Hole U1601A limited this type of analysis; thus, most of the AMS results were only meaningful for Hole U1601C. For Hole U1601C, the clustering of the shortest magnetic axis, $\kappa_{min}$, around vertical indicates that the direction of magnetic flow was subhorizontal. Particular regions, however, display elongated fabrics, or regions of greater anisotropy. The regions of magnetic elongation correspond well with the depths of recovered deformed gabbro units (200 and 600 mbsf). These observations suggest that different interval depths experienced different tectonic and/or alteration histories.