IODP Expedition 399: Building Blocks of Life, Atlantis Massif

Site U1309 Summary

Background and Objectives

Previous Drilling at Site U1309

Site U1309 is located on the central dome of Atlantis Massif, 14–15 km west of the median valley axis of the Mid-Atlantic Ridge (MAR), and ~5 km north of the Lost City Hydrothermal Field. The seafloor is interpreted to be a gently sloping, corrugated detachment fault surface. The site was established in Integrated Ocean Drilling Program (IODP) Expeditions 304 and 305 in 2004–2005, when the two main Holes U1309B and U1309D were drilled as well as five shallow and failed holes.

Expedition 304 established a hard rock reentry system comprising 25 m of 13⅜ inch casing in Hole U1309D using a hammer drill. During that operation, 4.5 m of casing was left protruding from the seafloor, and a reentry cone was successfully dropped onto the casing. The hole was then deepened to 131 meters below seafloor (mbsf). After carrying out operations at Sites U1310 and U1311, Hole U1309D was deepened to 401 mbsf and logged. Expedition 305 followed directly after Expedition 304 and deepened Hole U1309D to 1415 mbsf in two stages, with logging runs in the middle and at the end of coring. Hole U1309D was reentered and logged during IODP Expedition 340T in 2012 and had remained undisturbed from 25 February 2012 until operations during Expedition 399.

Hole U1309D sampled a continuous sequence of gabbroic rocks including troctolite and olivine-rich troctolite, olivine gabbros, oxide gabbros, and rare leucocratic intrusions. A few minor screens of mantle harzburgite are present in the upper 300 m of the section. Diabase/basalt intrusions with chilled margins form ~40% of the top 120 m of the sequence, with rare occurrences at greater depths. Many igneous contacts are present within the section, with units varying from centimeters to tens of meters in thickness. More evolved units generally (but not always) intrude into more primitive units.

Crystal-plastic deformation is restricted to narrow zones in the section, mainly above 300 mbsf. Cataclasis and fault breccia are present in several strands in the upper 80 m of the section, a fault zone at ~160 mbsf, and a prominent 6 m thick fault zone at 744–750 mbsf within a damage zone from 742–761 mbsf. A crystal-plastic deformation zone at 1100 mbsf is suggested by temperature logging and has a weak signal in the core.

Alteration is most extensive in the upper 300 m of the section, where clinopyroxene is usually at least partly altered to amphibole (hornblende and actinolite) in both gabbro and diabase. In olivine-bearing rocks, choronitic tremolite and chlorite form at the expense of olivine and plagioclase. Below 300 mbsf, this reaction only goes to completion around faults and gabbro contacts, and rodingitization of plagioclase to prehnite ± hydrogarnet driven by serpentinization of olivine is seen. The latest reactions and veins contain saponite and zeolites, and may be forming in near ambient conditions.

Temperature logging occurred at the end of Expedition 305 and again during Expedition 340T, seven years later. During Expedition 305, the temperature gradient was strongly affected by drilling, with a steep rise in the lowest part of the hole and a maximum temperature of 118.9°C at 1415 mbsf. During Expedition 340T, the temperature profile in the borehole water was assumed to have equilibrated with the rock and reached 146.2°C at 1405 mbsf. Below ~750 mbsf, the temperature gradient is linear, and a conductive regime is inferred. Above 750 mbsf, the temperature profile is curved, suggesting slow downward movement of fluid in the rock mass. Small excursions in temperature, seen at ~750 and 1100 mbsf, are inferred to be the result of influx of colder fluid.

Samples for microbiology were taken from a range of lithologies and depths during Expeditions 304 and 305. Cell counts were below detection limit ($<10^3$ cells/cm^3 rock). Microbial diversity was assessed using cloning and sequencing, terminal restriction fragment length polymorphism, and a microarray for metabolic genes ("GeoChip"). The low-diversity microbial communities consisted of lineages closely related to bacteria from hydrocarbon-dominated environments and known hydrocarbon degraders.

Objectives of Site U1309 Revisit

1) To sample fluids and obtain temperature data in the undisturbed borehole, and study geochemistry and microbiology of fluids at temperatures above and below the current known limit of life.
2) To mill out a caliper arm lost during Expedition 340T and believed to be in the bottom of Hole U1309D, leaving the hole in good condition for further operations.
3) To deepen the Hole by ~650 m to reach temperatures of ~220°C where active serpentinization reactions might be occurring, and where increasing amounts of mantle rock might be expected within the gabbroic sequence.
4) To drill an additional single bit hole at Site U1309, with the aim of sampling zones of fault-induced and reaction porosity for microbiology, not collected on Expedition 304.

Whereas our first two objectives were realized, Hole U1309D was only deepened by 83 m and a new shallow hole was not drilled. In light of the unexpectedly good results at Site U1601, the science party decided that achieving a deep hole in peridotite (the original aim of Expeditions 304 and 305) at Site U1601 should be prioritized.

Operations

Hole U1309D (first visit)

After the failure of releasing the reentry system in Hole U1601B on 24 April 2023, 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.

Bit Run 1: Temperature Logging and Fluid Sampling

The ship began its 2 nmi dynamic positioning (DP) move to Hole U1309D at 2353 h on 24 April and arrived at 0116 h on 25 April. A bottom-hole assembly (BHA) was assembled with a 9¼ inch clean-out bit (4⅛ inch inner diameter) and without a float valve to deploy the novel Multi-Temperature Fluid Sampler (MTFS), the Kuster Flow Through Sampler (Kuster FTS), and the Elevated Temperature Borehole Sensor (ETBS) on the coring line. The drill string was lowered at 0830 h, and the subsea camera with Niskin water sampling bottles attached to its frame was deployed at 1115 h. The ship was offset ~20 m from Hole U1309D to pump the "pig" tool to clean rust from the inside of the newly deployed drill string. The bit reentered Hole U1309D at 1455 h. The reentry cone was partly filled and blocked by a soft particulate deposit that was easily displaced upon bit entry into the cone. The Niskin bottles were triggered and the camera frame with the bottles was returned to the rig floor by 1620 h. The MTFS and ETBS were prepared on the catwalk, rigged up, and lowered down the drill pipe at 1815 h. The MTFS assembly descended in the open hole at a rate of 10 m/min, with 3 min temperature check stops every 100 m. The tool string tagged bottom at 1389 mbsf, indicating a 26 m thick fill at the bottom of Hole U1309D, and then ascended at a rate of 15 m/min in the borehole and 30 m/min in the water column. The tools arrived back on the rig floor at 0043 h on 26 April.

The tools were rigged down, and the ETBS was removed from the MTFS and connected to the two Kuster samplers. The two Kuster FTS clocks were set to sample at 411 mbsf (0310 h) and 739 mbsf (0330 h). The tool assembly was lowered down the drill pipe at 0207 h and was back on the rig floor at 0500 h. A second run of the Kuster FTS ETBS assembly was configured to sample at 1111 mbsf (0823 h) and 1320 mbsf (0846 h). It was lowered down the drill string at 0706 h and was back on the rig floor at 1225 h. On descent, the tool string traveled at a rate of 20 m/min, slowing to 15 m/min within 40 m of the desired sample depth to minimize hole disturbance. The tool was recovered at a rate of 10 m/min with 3 min stops every 100 m for temperature check measurements. The drill string was retrieved with the bit clearing the rig floor at 1620 h on 26 April, ending BHA run 1 in Hole U1309D on Expedition 399.

Bit Run 2: Milling

Next, we needed to remove a few tens of meters of fill from previous drilling in Hole U1309D during IODP Expeditions 304 and 305, as well as a logging caliper arm presumed to have been left in the hole at the end of IODP Expedition 340T. A BHA was made up with a 9⅝ inch concave mill and two junk baskets, and lowered to the seafloor at 1845 h. At 2120 h the subsea camera and two Niskin water samplers were deployed. At 0000 h on 27 April, Hole U1309D was reentered for the second time on this expedition. The camera and Niskin water sample bottles were recovered, and the drill string was further run into the hole. At 0800 h the bit tagged the top of the fill at 1379 mbsf (~37 m of fill). Milling and washing downhole proceeded expeditiously, the first 7–8 m at 8 m/h, and the remainder at 30 m/h. At 1007 h, the bit was ~1.5 m above the previously reported bottom of Hole U1309D (1415.5 mbsf). The first 10 min of milling near the bottom indicated erratic torque, presumed to be the result of encountering metal pieces lost on a previous expedition. The subsequent 3.5 h of milling indicated low and steady torque. The pipe was raised and lowered repeatedly for 1 h to fill the junk baskets, and a 30 bbl mud sweep completed cleaning operations in Hole U1309D. Retrieval of the drill string began at 1515 h and at 2200 h, the mill bit arrived at the rig floor where the junk baskets were emptied. Amongst dozens of rock pieces and bags of cuttings created during previous drilling on Expeditions 304 and 305, the junk baskets also recovered several metal pieces, including three 5 cm × 5 cm chunks. The metal pieces were identified as parts from the Versatile Seismic Imager (VSI) wireline logging tool that was damaged during Expedition 340T ~11 years ago.

Bit Run 3: Coring

At 2315 h the rig crew began assembling the rotary core barrel (RCB) BHA with a new C7 bit, which was complete at 0130 h on 28 April. The drill string and subsea camera were deployed, and at 0525 h Hole U1309D was reentered for the third time on this expedition. The camera was retrieved, and the bit was lowered until it reached a hard tag at 1410.0 mbsf. We dropped a core barrel, washed to 1415.5 mbsf, and began deepening Hole U1309D from where IODP Expedition 305 had ended. Coring proceeded until 1 May, when the bit had accumulated 50 h at bottom, and we decided to retrieve it. This coring bit run advanced Hole U1309D by 82.5 m, from 1415.5 to 1498.0 mbsf. Cores U1309D-279R through 313R recovered a total of 48.9 m, with core recovery ranging from 26% to 98% (average of 59% recovery). 30 bbl mud sweeps were pumped every ~5 m to keep the hole clean. At 1145 h we began retrieving the drill string and the bit cleared the seafloor at 1620 h.

This was a good opportunity to test the ETBS, which had malfunctioned on previous runs and had been worked on since. With the bit several meters above the seafloor, we installed the top drive again, installed the sinker bars, and deployed the ETBS to the end of pipe for ~10 min. The test results were negative and required additional repair efforts. At 1900 h we continued to retrieve the drill string, and the bit cleared the rig floor at 2245 h on 1 May, ending bit run 3 in Hole U1309D on this expedition.

During this first period of operations in Hole U1309D, the crew had established a plan and prepared equipment for a second attempt at setting a reentry system at Site U1601. Operations therefore continued in Hole U1601C from 1 May to 2 June.

Hole U1309D (second visit)

On 2 June, the ship returned to Hole U1309D for the last operation of Expedition 399, to take more borehole fluid samples from Hole U1309D using the Kuster FTS and then flush the hole rigorously. The ship had already moved over to Hole U1309D in DP mode by 1612 h on 2 June, while the drill string was being retrieved from Hole U1601C. A BHA was assembled with a clean-out bit, no float valve, and an oversized landing ring (logging configuration). At 1915 h the drill string was lowered to the seafloor, the subsea camera was deployed at 2130 h, and Hole U1309D was reentered for the fourth time on Expedition 399 at 2317 h. At 0045 h on 3 June, the drill string was positioned at 32 mbsf. Two Kuster FTS bottles were assembled with the ETBS and the Conductivity-Temperature-Depth (CTD) tool. The first run on the coring line was deployed at 0100 h and was back on the rig floor at 0315 h. The borehole water samples were taken at 200 and 400 mbsf. The tool string was retrieved and disassembled, the water samples and data were retrieved, and the tools were reassembled for the second run. The CTD was not included on subsequent runs because its temperature rating would have been exceeded at the deeper sampling stations. The second sampling run from 0400 h to 0645 h triggered one Kuster FTS at 550 mbsf and one at 736 mbsf. Ample time was available to redress the tools and conduct a third run from 0736 h to 1100 h. During this final run, the tools were not able to pass an obstruction at 1024 mbsf, and the samples were taken at 923 and 1110 mbsf instead of a deeper planned station. After conclusion of the sampling runs, the drill string was lowered to 1421 mbsf and washed down to the bottom of the hole at 1498 mbsf. Next, the hole was flushed with seawater 7× the borehole volume to leave behind as clean as possible a hole for potential future water sampling and temperature measurement operations. Final retrieval of the drill string from Hole U1309D began at 1945 h on 3 June and was completed with the bit clearing the rig floor at 0324 h on 4 June. The rig was secured for transit, and the vessel was underway at 0430 h, ending operations at Site U1309 and on Expedition 399. The vessel arrived in Ponta Delgada, Azores, Portugal on 8 June, with the first line ashore at 0748 h.

Principal results

Igneous Petrology

Deepening Hole U1309D from 1415 to 1489 mbsf during Expedition 399 recovered predominantly gabbroic rocks: gabbro (27%), olivine-bearing gabbro (59%), and olivine gabbro (12%), with small proportions of crosscutting diorite and diabase (1% and 2%, respectively). As observed for the 1415 mbsf interval drilled during IODP Expeditions 304 and 305, olivine-bearing rocks are abundant in the newly drilled interval. However, the proportion of gabbro below 1415 mbsf is significantly higher and the proportion of olivine gabbro is significantly lower than above that interval. In addition, many of the rock types recovered at shallower levels in Hole U1309D were not recovered during Expedition 399, including ultramafic rocks, troctolite, tonalite, trondhjemite, and oxide gabbros.

The main recovered gabbro body has internal gradational contacts between rocks with different grain sizes, mineral modes, and textures (subophitic to ophitic to poikilitic). This indicates that the different subunits form part of a continuum of crystallization within a single plutonic body, rather than representing discrete intrusions. In general, olivine was first to crystallize, followed by plagioclase and clinopyroxene. Crystallization continued as melt compositions evolved. This is evidenced by the common presence of zoning in plagioclase and late-stage crystallization of orthopyroxene. The general lack of the characteristic assemblage of amphibole+Fe-Ti oxide indicates that this late-stage melt did not generally evolve to the point of oxide saturation.

Following the accretion of the gabbroic units, two stages of additional magmatism occurred. First, diorite veins intruded, forming sutured and reactive contacts, which indicate that intrusion occurred when the gabbroic rocks were still at elevated temperatures. The final igneous activity is marked by the diabase dikes. The chilled margins of the diabase dikes with the gabbros attest to intrusion in a relatively cold environment. Furthermore, the thin section observations of entrainment of hydrothermally altered microxenoliths indicate that at least some diabase intrusions occurred after the host gabbroic rocks had already experienced hydrothermal alteration.

Alteration Petrology

Gabbroic rocks recovered from Hole U1309D during Expedition 399 show a low extent of alteration (<20 vol% secondary replacement) that slightly decreases downhole. An exceptionally high extent of alteration occurs at intervals where localized alteration associated with cataclastic deformation, prominent hydrothermal or magmatic veining, and patchy bleaching took place. Alteration minerals appear to have formed under static conditions, except for amphibole formation associated with localized deformation in cataclastic zones.

Zeolite, amphibole, chlorite, and composite amphibole-chlorite veins frequently occur throughout cores without systematic downhole distribution. Crosscutting relationships of veins indicate a sequence of generation stages from older to younger: 1) magmatic veins; 2) amphibole, chlorite, or amphibole-chlorite veins; and 3) prehnite-carbonate and zeolite veins.

Primary minerals in gabbroic rocks are variably altered to secondary minerals along grain boundaries, microcracks, or cleavage surfaces. In some cases, particularly in proximity to hydrothermal veins, complete replacement yields pseudomorphs after primary minerals. Olivine is replaced by serpentine + oxide/sulfide, talc + sulfide/oxide, clay + oxide/sulfide, and amphibole + oxide + chlorite. Fluid inclusions in olivine are locally abundant. Clinopyroxene and orthopyroxene are altered to amphibole, chlorite and/or talc. Plagioclase is altered to chlorite, amphibole, secondary plagioclase, prehnite, and zeolite.

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 took place at conditions ranging from amphibolite through greenschist to subgreenschist facies.

Structural Geology

Structural analysis of Cores U1309D-297R to 313R (1415–1498 mbsf) recovered during Expedition 399 reflects a temporal and spatial overlap in magmatism and semibrittle to brittle deformation processes in the footwall of an oceanic detachment system.

Magmatic fabrics in the recovered gabbroic rocks are dominantly isotropic, with grain size variations and rare diffuse contacts between grain size domains. Rare magmatic foliations, shown by a shape preferred orientation of plagioclase or pyroxene, have gentle to subvertical dips. Occasionally, diabase intruded the gabbroic rocks, postdating the brittle to semibrittle deformation.

Rare crystal-plastic deformation was only observed microscopically. Gabbroic rocks that appear undeformed at the macroscale infrequently display very low-strain crystal plastic deformation (deformation twinning and/or subgrains) in plagioclase. Localized fault rocks can display subgrain development and minor grain boundary bulging dynamic recrystallization in plagioclase related to brittle to semibrittle deformation of relict igneous plagioclase.

Brittle to semibrittle deformation is concentrated in two strands of a semibrittle shear zone between 1451 and 1460 mbsf (Sections U1309D-304R-2 to 306R-1) and 1464 and 1474 mbsf (Sections 307R-1 to 308R-1), with relatively undeformed rocks in sections above and below these intervals. The shear zones are characterized by brittle to semibrittle deformation over a significant range of intensities from fractures and microfaults, faults, and fault breccia, to formation of zones of cataclasite and phyllonite. Microscopic analysis of high intensity deformation zones shows localized plagioclase-amphibole cataclasite and amphibole phyllonite fault cores. Reverse shear sense was determined in rare cases where structural orientation was preserved in recovered intervals. Diabase dikes in some cases cut cataclastic zones.

The most abundant vein types include amphibole, chlorite, and zeolite veins, and minor prehnite and carbonate veins, formed across a broad range in temperature. Crosscutting relationships and vein deformation record that amphibole and chlorite veins are pre-/syn- and postdeformational. Additionally, amphibole-chlorite alteration of fractured rocks is typically undeformed. Low-temperature zeolite, prehnite, and carbonate veins are undeformed and therefore postdate deformation. Collectively, the deformation mechanisms in plagioclase and amphibole, taken with crosscutting relations between deformation, alteration, and vein generation, demonstrate that semibrittle deformation occurred at lower amphibolite to greenschist-facies conditions.

The cores reflect a down-temperature history from crystallization of gabbroic rocks, cooling with very limited deformation to lower amphibolite-upper greenschist facies conditions, followed by semibrittle deformation in a shear zone at lower amphibolite to greenschist facies conditions along shear planes with present-day dips of 10°–30°. Due to the depth of the interval 1415 to 1498 mbsf, it is unlikely that the reported semibrittle shear zone is directly related to the detachment fault exposed at the seafloor. The greenschist facies conditions of deformation suggest that Atlantis Massif continued to deform during the later stages of exhumation, followed by a phase of magmatism (diabase).

Geochemistry

Geochemical analyses were carried out on rock samples selected by the Geochemistry and Microbiology teams, and fluids collected during the two separate water sampling campaigns. Twenty-nine rock samples from Hole U1309D were analyzed for major and trace element concentrations and for their volatile element concentrations. These samples comprised: (1) one diabase, one leucocratic diorite, three olivine-gabbro, and 15 gabbro samples (including ten olivine-bearing gabbro samples) collected for rock geochemical studies; and (2) one olivine-gabbro and eight olivine-bearing gabbro samples analyzed as part of an interdisciplinary study of rock samples collected primarily for microbiological studies.

The analyzed samples do not display systematic chemical variations with depth except for those associated with the crosscutting diabase at 1417.9 mbsf and leucocratic diorite at 1443.8 mbsf.

Expedition 399 olivine-gabbros and gabbros have major and trace element compositions similar to those of the most primitive gabbros and the most evolved olivine-gabbros recovered at Site U1309 during Expeditions 304 and 305. They overlap in composition and are characterized by high Mg# (74–80) and Ca# (73–82) and low TiO_2 concentrations (0.26–0.50 wt%). Except for some microbiology samples that have H_2O up to 2.17 wt%, they have low H_2O contents similar to Hole U1309D gabbroic rocks sampled below 850 mbsf. The presence of H_2O indicates the replacement of primary minerals by hydrous minerals during hydrothermal alteration and weathering. The major and trace element compositions of Expedition 399 olivine-gabbros and gabbros provides no evidence of elemental remobilization associated with H_2O concentration variations, even for fluid mobile elements.

The analyzed leucocratic sample is the white part of a leucocratic diorite recovered at ~1444 mbsf. Its composition is that of an An45 plagioclase (Ca# 45) and, except for Sr, an element typically enriched in plagioclase, it is depleted in almost all trace elements. In that respect, it differs significantly from the previously analyzed Site U1309 leucocratic veins and dykes that represented the most enriched endmembers of the rocks recovered during Expeditions 304 and 305. The fine-grained diabase intruding the gabbroic rocks at 1417.9 mbsf has a basaltic composition characterized by high Mg# (69) and low TiO_2 concentrations (0.79 wt%). It represents one of the most primitive, depleted, and least altered endmember of the mid-ocean-ridge basalt (MORB) magmatic suite at Site U1309.

Based on their major and trace element compositions, Expedition 399 Hole U1309D diabase and gabbroic rocks form a coherent suite with the diabase, basalt, and gabbroic rocks sampled at the same site during Expeditions 304 and 305, indicating a cogenetic origin for these mafic rocks.

In the initial fluid sampling campaign at Hole U1309D, the inaugural deployment of the MTFS successfully recovered fluids from four depths and the Kuster FTS samplers recovered fluids from an additional four depths. Both samplers returned with abundant solid material that was likely a mixture of drilling mud, cuttings from the borehole, bottom fill, and grease. The fluids appear to be a mixture of seawater, formation water, and a fluid that reacted with fill at the base of the hole. The second fluid sampling campaign at the end of the expedition collected an additional three Kuster FTS samples with full volumes, and three with incomplete recovery. The samplers did not return large amounts of solid material from these deployments, and the fluids were notably clearer.

Microbiology

Microbiological investigations at Hole U1309D were designed to explore potential signs of recent or past life at extreme temperatures, in particular the shallowest rocks that may have been exposed to borehole water during the 18 years since Expedition 305. 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 nine microbiology whole-round samples were collected from Cores U1309D-297R to 313R. Eight of the samples are olivine-bearing gabbro and one is olivine gabbro.

Each of the nine samples was rinsed, photographed, and separated into exterior and interior sections according to our standard methodology. Perfluorocarbon tracer (PFT) levels in the interior sections of all nine samples were below detection or at very low levels (max 0.1 ppb). In contrast, PFT was detectable in the exterior shavings of all microbiology whole-round samples except one, ranging from trace levels to 22 ppb. The consistent reduction of PFT levels from exterior shavings to interior zones affirms the efficacy of our procedures for limiting contamination into the interior zones of the core samples.

Subsamples from each of the nine samples were collected for cell counts, DNA sequencing, lipid characterization, and organic carbon analyses. Subsamples for single-cell activity assays were collected from six of the nine samples. Stable isotope tracer experiments were conducted with four of the samples. Subsamples for virus counts, enrichment cultivations, and scanning electron microscope (SEM) imaging were collected from the first five samples. High-pressure cultivation experiments were conducted with subsamples collected from Cores U1309D-297R and 298R.

Water samples collected with Niskin bottles, the MTFS, and the Kuster FTS were subsampled for microbiological analyses intended to characterize the extent, diversity, and activity of microbial communities within Hole U1309D. Subsamples for cell counts and single-cell activity assays were collected from all four of the high-volume MTFS samples (bottles 1, 2, 4, and 5) and all Kuster FTS and Niskin samples. In addition, MTFS bottle 2 was subsampled for virus counts, enrichment cultivations, high-pressure cultivations, and stable isotope tracer experiments. Water from MTFS bottle 4 (260 mL), the three Kuster FTS bottles (250 mL each), and all Niskin bottles (3–5 L) were filtered through a 0.2 µm Sterivex filter cartridge intended for DNA sequencing.

Petrophysics

The petrophysical properties of gabbro in Hole U1309D were characterized through measurements on whole-round cores of natural gamma radiation (NGR), magnetic susceptibility (MS), and gamma ray attenuation (GRA) density over the Interval U1309D-297R through 313R (1415–1498 mbsf). Discrete measurements were completed on cubes and included wet mass, dry mass, and dry volume for the calculation of density and porosity, and *P*-wave velocity. Core pieces from section halves were selected for thermal conductivity measurements. Downhole temperature logs were completed. No other petrophysical logging was attempted in this hole.

Bulk density from whole-round measurements ranges from 2.6 to 2.9 g/cm^3 and generally increases with depth. Some intervals deviate from this trend, including a general downhole decrease in density in the Interval U1309D-302R through 303R (1441–1445 mbsf), which is also mirrored in the grain density measured on discrete cube samples.

A total of 31 discrete cube samples were analyzed. Grain density ranges from 2.87 to 3.03 g/cm^3, with an average of 2.94 ± 0.08 g/cm^3. Grain density and bulk density generally increase with depth. Grain density is negatively correlated with porosity, with porosity generally decreasing with depth. Porosity ranges from 0.5% to 2%, with an average of 1.27 ± 0.79%. The highest porosity is measured in Interval U1309D-302R through 305R (1441.2 to 1455.0 mbsf), which also includes an altered felsic dike that has a grain density of 2.55 g/cm^3 and a porosity of 5%.

P-wave velocity was measured on 30 discrete cube samples (1 diabase, 3 olivine-gabbro, and 26 gabbro) along the three principal directions *x*, *y*, and *z* in the core reference frame (CRF). The average *P*-wave velocity of the three-axis on each sample ranges from 4964.7 m/s to 5894.6 m/s, the average is 5476.0 m/s, and the apparent anisotropy of *P*-wave velocity ranges from 4.1% to 7.0%.

MS is relatively low, reflecting a relatively low proportion of magnetite in these rocks. Pass-through loop magnetic susceptibility (MSL) is typically under 500 instrument units (IU) and point magnetic susceptibility (MSP) is typically below 1000 IU. The highest values for MSL and MSP are in Section U1309D-311R-1, with a value of ~1500 IU for MSL and ~6500 IU for MSP, indicating more abundant magnetite.

NGR is very low with most values <0.5 counts/s. Thermal conductivity was measured on 17 archive-half core pieces >10 cm in length. Samples of representative lithologies for the hole were measured. Values for all pieces range from 2.14 to 2.63 W/(m·K) with a mean of 2.35 ± 0.14 W/(m·K). No obvious trend with depth or lithology exists.

Borehole fluid temperatures were measured in Hole U1309D prior to coring. The best results were recorded with the first run down the hole, with the ETBS attached to the MTSF. Values for the entire borehole during the down run range from 6.7°C at the seafloor to 139.6°C near the bottom of the hole. The resulting profile shows slight curvature in the upper ~580 mbsf, transitions into a more linear gradient deeper than 580 mbsf, and continues linearly to the bottom of the hole. The profile in the deeper half of the hole indicates a gradient of ~114°C/km. The temperature profile is very similar to that recorded during Expedition 340T, indicating no significant changes in hydrological or heat flow regime in the last 11 years.

Paleomagnetism

Remanence measurements were made on archive section halves from Hole U1309D, adding to the breadth of knowledge for the preexisting hole. These measurements generated 6,281 new measurement points downhole. The mean natural remanent magnetization (NRM) inclination was determined to be -25.7° ± 12°. Stronger alternating field (AF) steps of 10–15 mT shift and narrow the distribution towards the expected geocentric axial dipole (GAD) value of −49°. At the AF step of 50 mT, the mean inclination became −34.4°. This shallower inclination value relative to the expected value is consistent with previous work on the hole. The cause for shallowing was interpreted to be the result of tectonic rotation.

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, paleomagnetic cube samples were pretreated with liquid nitrogen dunking as a way of reducing the drilling overprint. Multiple remanence directions were recorded, but the direction of the most coercive components was consistent with the mean inclination direction, as put forth by the archive section half analysis. The bulk remanence of these rocks is carried by magnetite. The intensity of magnetic remanence varies downhole, ranging from 0.02 to 3.81 A/m with a mean of 0.90 A/m, indicating varying distributions of magnetite. Results from the isothermal remanence experiments provide evidence for predominantly multidomain and minimal single domain magnetite grain populations.

Anisotropy of magnetic susceptibility (AMS) data indicate predominantly oblate magnetic fabrics. The clustering of the shortest magnetic axis, κ_{min} around the vertical indicates that the direction of magnetic flow was horizontal. The degree of anisotropy averages 1.121 ± 0.075 (n = 50) with low and high values ranging from 1.029 to 1.424. The average value of P_j indicates that most susceptibility tensors are moderately anisotropic but significantly higher degrees of anisotropy are noted in many coarse-grained gabbroic samples.