IODP Expedition 402: Tyrrhenian Continent–Ocean Transition

Site U1616 Summary

Background and Objectives

Site U1616 (proposed Site TYR-15A) is one of four drill sites in the Vavilov Basin targeting exhumed mantle peridotites. Site U1616 is near the western end of the planned east–west transect across the Vavilov Basin and is located on an irregular basement high, interpreted to be the uplifted footwall of a long-offset low-angle detachment fault that exhumed the mantle. Just like the other sites in the Vavilov Basin, the scientific objectives of Site U1616 were (1) to date the oldest sediment above the basement contact to constrain the timing of mantle exhumation using biostratigraphy and magnetostratigraphy; (2) to sample sediments and pore fluids above the basement contact to investigate fluid-rock interactions; and (3) to recover basement samples to determine the heterogeneous composition of the exhumed mantle, its degree of serpentinization and alteration, and its pattern of structural deformation.

After two rotary core barrel (RCB) bottom-hole assemblies (BHAs) were lost when they were irremediably stuck in Holes U1612A and U1614C in the Vavilov basin, we were forced to reevaluate the drilling plan. We decided not to drill any sites at the northern end of the north–south Vavilov Basin transect (proposed Sites TYR-17A, TYR-18A, and TYR-19A) because the thick sediment cover (~500–1000 m) was likely to contain unstable volcaniclastics. We concentrated instead on Sites U1615 and U1616, located on basement highs in the east–west transect where the estimated sediment cover is substantially thinner (~200 m). The original order of drilling operations at Site U1616 was reversed to core a hole first with the advanced piston corer/extended core barrel (APC/XCB) system. The expected high recovery of the sediment interval in this hole would provide a high-quality record above the sediment/basement interface and would allow for determining the extent and depth distribution of unconsolidated volcaniclastics. We would then compare the results with those obtained in a similar APC/XCB hole drilled at Site U1615, also located in the east–west transect about 10 km east of Site U1616. Based on the coring results, we planned to select one of Sites U1615 or U1616 to install a casing string that would reach below the base of the problematic volcaniclastics. This second hole would then be cored with the RCB system starting above the sediment/basement interface, with the goal of recovering the target 140 m thick basement interval. Finally, downhole wireline logging was planned. Site U1616 was selected for the casing installation and was cored ~124 m into the basement. Downhole logging was attempted with limited results.

Operations

The vessel arrived at Site U1616 on 10 March 2024, following a 5 nmi transit from Site U1615 completed in dynamic positioning (DP) mode at 0315 h. The top drive was picked up and drill pipe was spaced out to spud, filling the drill string with the perfluorodecalin (PFD) microbial contamination tracer prior to coring. Hole U1616A was spudded at 0530 h, recovering the mudline and penetrating 2.7 m into the formation (101% recovery), placing water depth as 3567.0 m. APC coring continued through Core U1616A-6H, reaching a depth of 50.2 meters below seafloor (mbsf) and recovering 47.72 m of sediment (95%) overall. A formation temperature measurement was made with the third-generation advanced piston corer temperature (APCT-3) tool during Core 4H. Ship heave intensified throughout the morning and, after recovery of Core 6H, the decision was made to pull out of the hole and wait on weather (WOW), thereby ending Hole U1616A.

Hole U1616B was spudded at 1500 h on 10 March, after 2 h of WOW. This hole began with a drilled interval (U1616B-11) to a depth of 31.2 mbsf, where APC/XCB coring resumed with Core U1616B-2H. Cores 2H–6H advanced 47.5 m and recovered 34.25 m of sediment (72%). An APCT-3 measurement was made during collection of Core 4H. After Core 6H, a half-length APC attempt misfired and resulted in a dropped core barrel. Two wireline runs were required to retrieve the empty barrel. Cores U1616B-7X through 29X, taken with the XCB system, advanced the hole to a final depth of 302.6 mbsf. Recovery was poor in Cores 7X–10X (3%) but improved in Cores 11X–27X (72%). A hard contact was reached during XCB coring of Core 28X and rate of penetration (ROP) slowed. The core advanced 8.3 m after an hour of drilling and was retrieved with only 6% recovery, but contained clasts identified as peridotite breccia. A final core, Core 29X, was collected to verify the basement contact. Coring was terminated and we then began tripping pipe back to the surface. The bit cleared the rig floor at 1700 h on 12 March, ending Hole U1616B. Overall in Hole U1616B, a 271.4 m interval was cored with 156.58 m of core recovered (58%). Nonmagnetic core barrels were used for all APC cores, and all full-length APC cores were oriented. The PFD microbial contamination tracer was pumped with the drill fluid throughout coring.

Site U1616 was selected for the reentry system and casing installation due to the relatively high recovery in the sediment column compared to Site U1615 (58% in Hole U1616B compared to 38% in Hole U1615A). Additionally, the basement contact is deeper than anticipated and was not reached after 300 m of penetration in Hole U1615A. Finally, Site U1616 contains less volcaniclastic gravel than Site U1615, which can contribute to hole instability.

Following operations in Hole U1617A between 12–16 March, the vessel returned to Site U1616. The 40.1 nmi transit from Site U1617 was completed at 0112 h on 17 March.

After arriving on site, the vessel transitioned to DP mode and preparations began for a jet-in test to verify that the full 64.64 m of 16 inch casing could be washed in. The upper guide horn was removed and a BHA with an 18½ inch tricone bit was made up. We tripped pipe toward the seafloor and spudded Hole U1616C at 1115 h on 17 March. The jet-in test was successful, penetrating 76.9 m into the sediment in ~3 h. Pipe was tripped back to the surface and the bit was recovered to the rig floor at 2215 h, ending Hole U1616C. Preparations then began for the reentry system and casing installation planned for Hole U1616D.

With the reentry cone positioned on the moonpool doors, the 64.64 m of 16 inch casing that comprised the first casing string was run through the moonpool and hung in the reentry cone. The string consisted of five joints of 16 inch casing and several 16 inch pup joints that would extend the length of the string, past a layer of volcaniclastic gravel at ~60 mbsf that may cause hole instability. The stinger with the running tool and BHA were made up and latched into the reentry cone with the DrilQuip (DQ) running tool. The moonpool doors were opened and the reentry system was lowered toward the seafloor. The vibration isolated television (VIT) camera system was launched to monitor the installation of the reentry cone on the seafloor and the release of the running tool from the reentry cone.

Hole U1616D was spudded at 2000 h on 18 March and the casing was successfully jetted in to 64.64 m, such that the reentry cone was sitting on the seafloor. From 0430 to 0545 h on 19 March, we attempted to unlatch the running tool from the DQ reentry cone and casing, but we were unable to rotate it. Consequently, we made the decision to recover and inspect the reentry system and then redeploy in Hole U1616E. The casing was pulled out of the hole, experiencing strong overpull at ~10 mbsf. The VIT camera system was recovered and pipe was tripped back toward the surface. At 1400 h on 19 March, the reentry cone was brought back up through the moonpool and landed on the moonpool doors. We observed that all of the 16 inch casing string below the 20 to 16 inch crossover was lost. It is likely that the overpull experienced while pulling out of Hole U1616D was due to the casing detaching. The bit was recovered onto the rig floor at 1800 h, ending the hole. Two bent drill collars were removed from the BHA prior to making up a new BHA and latching it back into the reentry cone.

The reentry cone with the remaining ~5 m of 20 inch casing was lowered through the moonpool and we began tripping pipe toward the seafloor to install the reentry cone in Hole U1616E. The VIT, with the Conductivity-Temperature-Depth sensor and Niskin bottle water sampler attached to the frame, was launched at 2330 h and lowered to observe casing installation and release. Hole U1616E was offset 40 m west of Hole U1616D to avoid encountering any of the lost casing string that might be lying on the seafloor.

Hole U1616E was spudded at 0445 h on 20 March, with the 20 inch casing set at a depth of 5.5 mbsf. At 0545 h, the running tool successfully unlatched from the casing. We then pulled out of the hole, recovered the VIT, and tripped pipe back to the surface.

We began tripping pipe toward the seafloor, and at 2130 h we launched the VIT to guide reentry. The hole was reentered at 0120 h on 21 March and the VIT camera system was recovered. The hole was drilled to 250 mbsf, including a 30 m rathole to allow for fall-in from unstable layers within the sediment column. The drill ahead finished at 1130 h and the hole was swept with sepiolite mud and then displaced with 170 bbl of barite mud to keep the hole open during casing installation. We then pulled out of the hole and began tripping back to the surface. The VIT was deployed to monitor the bit clearing the reentry cone and the position of the cone on the seafloor, given the shallow depth of the first casing string.

The 13⅜ inch casing was rigged up and run, and the casing landed on the moonpool doors. The stinger and BHA were made up and run through the casing, and the stinger was latched into the casing hanger. We then began tripping pipe toward the seafloor, and we launched the VIT camera system to facilitate reentry in Hole U1616E. We finished tripping pipe to seafloor and reentered Hole U1616E at 1658 h on 22 March. The casing was washed in to a depth of 219.4 mbsf, landed in the reentry cone, and released at 2045 h. This casing depth successfully sealed off the volcaniclastic gravel (~60 mbsf) and tuff (~196–206 mbsf) layers that were predicted to pose a risk to hole stability.

Following the recovery of the drill string, a BHA with an RCB bit was made up and tripped toward the seafloor. Reentry occurred at 1628 h on 23 March, with the VIT camera system deployed to facilitate the process. The VIT was then recovered prior to drilling. We washed down the distance from the end of the casing (219.4 mbsf) to the bottom of the drilled interval (250 mbsf), encountering fill just below the casing shoe. A center bit was deployed to aid in washing down through the fill, and a 40 bbl sweep of sepiolite mud was pumped at the bottom of the hole to further clear the hole.

RCB drilling in Hole U1616E commenced at 2200 h on 23 March. Cores U1616E-2R through 23R penetrated from 250.0 to 371.0 mbsf. Cores 2R and 3R recovered 5.08 m of sediment from a 19.6 m advance (26%). A hard contact was encountered in Core 4R between sediment and a peridotite breccia, and recovery in Cores 4R–9R was very low (10%). All cores after Core 4R were taken as half advances to improve recovery. Drilling parameters and formation lithology became more consistent starting from Core 10R (303.5 mbsf), which was designated as the top of basement and which marks a transition from breccia into peridotite. Cores 10R–23R advanced 67.5 m into basement and recovered 17.5 m of hard rocks (26%).

During the drilling of Core U1616E-23R, the drill string experienced high torque and overpull at the bottom of the hole. Attempts to clean the hole bottom of any debris were unsuccessful and coring was terminated in favor of logging after about 3 h of effort. Core 23R ultimately recovered 0.15 m of rock out of a 2.8 m advance (5%). Overall, Hole U1616E contained a 121.0 m cored interval with 25.87 m (21%) recovered. All cores were taken with nonmagnetic core barrels.

The hole was conditioned for logging with a 40 bbl sweep of sepiolite mud and reaming to flush out cuttings and debris. The VIT was deployed and we pulled the drill string out of the hole, clearing the seafloor at 0545 h on 26 March. The vessel was offset away from the reentry cone and the bit released on the seafloor. Once this operation was successfully completed, we reentered Hole U1616E at 0815 h and recovered the VIT.

The triple combo logging tool string was rigged up and deployed at 1230 h on 26 March with the end of the drill pipe set at 266.6 mbsf, ~10 m above the contact between sediment and breccia. The tool encountered an obstruction at 306.7 mbsf, directly below the breccia/basement contact at 303.5 mbsf. We made the decision to recover the triple combo tool string, lower the drill pipe past this interface to a depth of 309.8 mbsf, and attempt a second logging run. The tool string was deployed for this second logging run at 1900 h, reaching a depth of 251.8 mbsf where it encountered an obstruction inside of the drill pipe. Attempts to clear the obstruction via circulation were not successful, with the pipe holding ~500 psi of pressure. Consequently, we ended logging operations and began pulling the triple combo string out of the hole. After recovery of the tool string, the circulating head was rigged up and 1000 psi was applied to the drill pipe to clear the obstruction. The drill pipe was then recovered with the end of pipe clearing the seafloor at 0245 h on 27 March. The end of pipe cleared the rotary, and the rig floor was secured for transit at 0925 h, ending that set of operations at Hole U1616E.

A plan to drill ahead through this interval of high torque using a tricone bit was formulated, but we decided to drill a second hole first at Site U1617 using the RCB system to attempt to recover the complete Messinian succession and to reach the underlying basement. After completing operations at Site U1617, the vessel returned to Site U1616. The transit included surveying with the 3.5 and 12.0 kHz sonar systems over a region of geological interest. The addition of the survey resulted in a 43 nmi transit that was completed at 0324 h on 1 April at an average speed of 11.3 kt.

Once positioned over Hole U1616E with the vessel in DP mode, a BHA with a 9⅞ inch tricone bit was made up and pipe was tripped toward the seafloor. The VIT camera system was launched to observe reentry. Hole U1616E was reentered at 1400 h on 1 April, the VIT was recovered, and drill pipe was tripped toward the hole depth of 371.0 mbsf. Ledges or obstructions in the hole were encountered starting at 254.8 mbsf;

the top drive was picked up and drill fluid was circulated to clear out the hole. The hole was reamed and washed to a depth of 371.0 mbsf and then was drilled from 371.0 to 400.0 mbsf (drilled Interval U1616E-241). We tripped pipe out of the hole, recovered the tricone bit, and made up a RCB BHA. We began tripping the pipe back toward the seafloor and launched the VIT camera system to facilitate reentry into Hole U1616E. Reentry occurred at 2208 h on 2 April and the VIT was recovered.

Cores U1616E-25R through 30R were all taken as half advances, penetrating 27.2 m deeper into basement and recovering 5.24 m of mantle rocks (19%). The final hole depth was 427.2 mbsf, including 123.7 m penetration into the basement below the peridotite breccia. ROP was 12.1 m/h, but the frequent wiper trips and mud sweeps required to keep the hole stable consumed significant time. During the recovery of Core 30R, the drill pipe was pulled up above the hole bottom in order to circulate drill fluid. For the next ~9 h, we reamed and cleaned the hole in an effort to remove cuttings and/or fill, but we were unable to reach hole bottom again. At 1000 h on 4 April, the decision was made to terminate coring in Hole U1616E and begin logging operations. A ghost core, Core U1616E-31G, was recovered, containing 0.78 m of rubble from an unknown depth within the hole.

Because of the challenging hole conditions, we elected to trip pipe fully back to the surface and reenter Hole U1616E with a logging bit that would give us greater ability to work through obstructions. The BHA with the logging bit was deployed and, while pipe was being tripped toward the seafloor, the VIT camera system was launched to facilitate reentry. The seventh reentry into Hole U1616E occurred at 0538 h on 5 April and the VIT was recovered. We picked up the top drive and used it to lower the drill string with the logging bit to 317.1 mbsf before racking the top drive again.

We deployed the standard triple combo tool string, without the radioactive source in the Hostile Environment Litho-Density Sonde due to concerns about hole stability. The bottom of the triple combo tool string passed ~25 m out of the logging bit, reaching a depth of 342.0 mbsf in the open hole before an obstruction was encountered and the entire tool string was recovered. The hole was reamed from 317.1 to 417.0 mbsf, where we encountered significant fill, ~10 m above the total hole depth. We then pumped a mud sweep to condition the hole prior to pulling the pipe back up for the second logging attempt; however, we lost rotation and became stuck at a depth of ~353 mbsf. We were able to work the stuck pipe and eventually back ream to the casing shoe. These unsafe hole conditions deep within the hole precluded further logging efforts. Pipe was tripped back to the surface and the drill bit was recovered onto the rig floor at 0630 h on 6 April, ending operations at Site U1616.

Total operational time at Site U1616 was 18.0 d over the three visits to the site.

Principal Results

Lithostratigraphy

Sediment recovered from Holes U1616A, U1616B, and U1616E was split into four units based on lithology. Unit I is divided into four subunits. In Hole U1616A, Subunit IA is characterized by nannofossil ooze and some silty sand with volcaniclastics. Subunit IB is described from Holes U1616A and U1616B. It contains volcaniclastic-rich sandy silt, volcaniclastic-rich sand, and volcaniclastic-rich gravel in Hole U1616A, whereas it lacks the volcaniclastic-rich sandy silt in Hole U1616B. Subunit IC is composed of silt with volcaniclastics and volcaniclastic-rich sand. Subunit ID also contains silt with volcaniclastics, but with an increased abundance of foraminifera-rich silt. Volcaniclastic-rich nannofossil ooze, volcaniclastic-rich sand, tuff, nannofossil ooze, nannofossil chalk, and sapropel layers are also described in Subunit ID.

Unit II is present in both Holes U1616B and U1616E; it contains nannofossil chalk, volcaniclastic-rich sand, foraminifera- and glauconite-rich nannofossil chalk, and nannofossil ooze with foraminifera. Unit III contains dolomitic-rich nannofossil ooze with foraminifera and is described in both Holes U1616B and U1616E. Dolomite is present in Hole U1616E. Unit IV was also described in Holes U1616B and U1616E, and it is characterized by fine-grained consolidated breccia.

Biostratigraphy

Operations at Site U1616 recovered sediment in Holes U1616A, U1616B, and U1616E. Samples from Hole U1616A consist of nannofossil ooze layers (Samples 402-U1616A-1H-CC and 2H-CC) assigned to the Holocene–Middle Pleistocene (<0.5 Ma) MPle2b foraminiferal biozone based on well-preserved planktic foraminifera marker species. The succession in the interval below (Samples 3H-CC to 6H-CC, to a depth of ~50 mbsf) predominantly contains volcanoclastic sediments that cannot be assigned to any biozones. Sediment from core catcher Samples U1616B-2H-CC to 15X-CC are also predominantly volcanoclastic in nature. However, a few nannofossil ooze layers found within the sections allowed for the identification of the Middle Pleistocene MPle2a sub-biozone. The lower half of the cored interval in Hole U1616B (Samples U1616B-16X-CC to 29X-CC) contains nannofossil ooze with intermittent volcanoclastic sediment layers. This succession between Samples U1616B-16X-CC and 22X-CC appears to be continuous and is assigned to the Calabrian MPle1 biozone (0.934–1.79 Ma). An ~1–1.2 Ma hiatus is found between Samples 22X-CC and 23X-CC. Below this hiatus, the sediments appear to be continuous and are Piacenzian (Samples 23X-CC to 26X-CC; MPl5 biozone; ~3.6 Ma) to Zanclean (Samples 27X-CC to 29X-CC; MPl4 biozone;

~3.85 Ma) in age. Hole U1616E was drilled using the RCB system, with the goal of recovering the sediment/basement interface and underlying mantle rocks. The layers above the basement rocks are Piacenzian (<3 Ma) in age, identified by well-preserved marker foraminifera species.

Five samples from Hole U1616A, 20 from Hole U1616B, and five from Hole U1616E were examined for the calcareous nannofossil content. The succession of the upper part of Hole U1616A is Chibanian–Holocene age (biozones MNQ21, MNQ20, and MNQ19d). The upper part of the sediment interval sampled in Hole U1616B is volcanoclastic sediment of Calabrian–Chibanian age (Early/Middle Pleistocene) ranging from biozone MNQ19d to MNQ19b. It is characterized by a high sedimentation rate (~152 m/Ma) probably due to the presence of mass transport deposits (MTD) and/or slumps. The ~1.2 Ma long hiatus between Samples U1616B-22X-CC and 23X-CC observed in the planktic foraminifera data is also evident from examination of the calcareous nannofossils. The lower part of Hole U1616B (from ~235 to ~290 mbsf) is represented by a continuous succession assigned to the MNN15b and MNN15a biozones (Piacenzian–Zanclean, 2.82–3.56 Ma) and is characterized by an average sedimentation rate of ~55 m/Ma. In Hole U1616E, the sediments directly overlying the peridotite breccia are assigned to the MNN16 biozone of Piacenzian–Zanclean age (2.51–2.82 Ma), thus highlighting a diachroneity of about 1 Ma with respect to age of sediments above the basement in Hole U1616B. However, both holes had a recovery of <10% in the cores across the sediment/breccia interface.

Paleomagnetism

Sediment in Holes U1616A and U1616B shows normal inclination throughout the succession, measured both by scanning the archive halves on the superconducting rock magnetometer and from the analysis of discrete cubes. Sporadic reversals in the sediment are correlated with the large deposits of volcanic gravel and with the extreme drilling disturbance present in Sections U1616B-25X-5 and 26X-2, and they are attributed to the poor quality of natural remanent magnetization measurements across these intervals.

Mantle rocks from Hole U1616E are also of normal polarity, differing from what is observed in peridotites recovered from Hole U1614C. Isothermal remanent magnetization and anhysteretic remanent magnetization experiments were conducted to determine magnetic carriers in the peridotites. The results show that magnetic mineralogy is more homogenous at Site U1616 compared to Site U1614.

Igneous and Metamorphic Petrology

As at Site U1614, mantle peridotites in Hole U1616E were recovered in contact with the sediments, except that the sediment/peridotite interface at Site U1616 is marked by a basal breccia. The lithology of the igneous rocks differs significantly between the upper and lower sections of Hole U1616E. The boundary between the upper section and the lower section is an interval drilled without coring from 371 to 400 mbsf.

Hole U1616B recovered an intact primary contact between lithified dolomitized sediments and a 20 m thick basal breccia, constituted of angular clasts of basalts and mantle peridotites. The peridotite clasts in the basal breccia at Hole U1616E are classified as lherzolites and harzburgites with the presence of minor plagioclase, embedded in a carbonate-rich matrix. A similar contact between sediments and highly serpentinized peridotites was recovered previously at Site U1614, where the basal polymictic breccia was found to be in direct contact with the dolomitic nannofossil ooze and a thin layer of lithified dolomite at 270 mbsf. In Hole U1616E, the breccia was recovered in Cores U1616E-3R to 9R. The clast size increases downhole, and the clasts consist mostly of harzburgites, exceptionally fresh diabase, and olivine-bearing gabbro. The top of the mantle peridotite section is at 303.5 mbsf.

Unlike in Hole U1614C, the mantle peridotites sampled from the upper section of Hole U1616E are relatively more homogeneous in composition and are dominated by harzburgites, with thin layers of lherzolites and dunites. Plagioclase-bearing peridotites are not observed in the mantle peridotites sampled from the upper section of the hole. Another feature that contrasts with Hole U1614C is the occurrence of diabase and gabbroic intrusives in Hole U1616E, with the gabbros altered to rodingites. Thin mica-bearing mafic intrusions are also rare in Hole U1616E compared to Hole U1614C. Additionally, Hole U1616E differs from Hole U1614C in terms of style of alteration, with the former having an overall lower degree of serpentinization, but more intense oxidation. The intervals of oxidized mantle peridotites in the upper section of Hole U1616E are often rich in carbonate veins, ranging from a few centimeters to submillimeters in thickness. Peridotite alteration in the upper section of Hole U1616E is significantly different compared to Hole U1614C, with alteration being mostly static serpentinization with pervasive carbonate veins lacking any significant ductile shearing. The bottom of the upper section of Hole U1616E is characterized by two layers of tectonic breccia, showing millimeter- to centimeter-scale clasts of angular peridotite in a carbonate matrix. Brittle deformation is observed in several locations throughout the section, mostly in between gabbroic veins and peridotites. Ductile deformation, on the other hand, is nearly absent in the upper peridotite section, whereas ductile deformed peridotites are present in the lower section.

The lower section of the hole was recovered beneath a drilled interval (371–400 mbsf). The section consists mostly of plagioclase-bearing harzburgites and lherzolites, with a substantial number of gabbroic intrusions. Notably, these plagioclase-bearing lithologies are absent in the upper section of Hole U1616E (303.5–371 mbsf). A significant portion of the peridotites in the lower section are intruded by mafic lithologies such as olivine gabbro, gabbro, diorite, and diabase/dolerite.

Structural Geology

Structural features were measured and described for sediment recovered in Holes U1616A and U1616B as well as the carbonate breccia and variably weathered serpentinized peridotites recovered in Hole U1616E.

The main structural feature observed in the sedimentary sequence was the finely laminated sediments interlayered by MTDs. No significant fault intersects the sedimentary section at Hole U1616B. Synsedimentary faults are locally observed to offset the bedding by about 10 mm. The sedimentary sequence is divided into two domains based on the bedding dip: Domain I is characterized by subhorizontal bedding, while Domain II is characterized by moderately dipping beds and laminations.

The sedimentary sequence lays on top of an ultramafic igneous basement. The contact is marked by a breccia composed of carbonate cement and clasts of peridotite. The basement is characterized by weakly deformed peridotites locally intruded by mafic intrusions. The alteration pattern is mostly marked by weathering and carbonate impregnation. In the peridotite interval, we measured various deformation structures, including crystal-plastic and brittle deformation, fractures and microfaults, magmatic intrusions (gabbroic, pyroxene-rich), and metamorphic veins (mainly serpentine and carbonate).

Sediment and Pore Water Geochemistry

A total of 25 whole-round core samples were collected at Site U1616 for extraction and analysis of interstital water (IW) and corresponding bulk sediment chemistry. This total includes four IW samples from Hole U1616A between 1.26 and 26.17 mbsf and 18 samples from Hole U1616B between 65.20 and 280.65 mbsf.

The IW alkalinity varies from 0.9 to 8.1 mg/L, increasing sharply from 3.2 mg/L near the seafloor to a maximum value of 8.1 mg/L at 26.17 mbsf, corresponding to the boundary between lithological Units IA and IB. Alkalinity then exhibits a decreasing trend toward the base of the cored sediment interval, with values less than 2 mg/L below 138.67 mbsf. The pH and salinity values show little variation, ranging from 7.2 to 7.9 and 37.0 to 40.0, respectively. Salinity increases across the lower part of lithological Unit IC (138.67–210.55 mbsf). The concentrations of sodium (Na^+) and chloride (Cl^-)

vary from 478.28 to 557.90 mM and 590.81 to 637.20 mM, respectively. Their depth profiles follow salinity changes, with elevated concentrations at the middle to lower sections of the lithological Unit IC. The profile of sulfate mirrors alkalinity values with depth, decreasing significantly from a maximum of 31.17 mM to a minimum of 21.30 mM at 26.17 mbsf. Below that depth, sulfate increases gradually to 30.13 mM at the base of the cored interval.

Dissolved magnesium (Mg^{2+}) and calcium (Ca^{2+}) show opposite concentration patterns with depth. Mg^{2+} decreases downhole from 57.25 mM near the seafloor, reaching a minimum of 18.00 mM at 148.60 mbsf. Below that depth, it shows an increasing trend, with a peak concentration of 50.06 mM at the base of the cored sediment interval. In contrast, Ca^{2+} increases downhole to a maximum of 36.94 mM at 148.60 mbsf, and then decreases to 16.71 mM at the base of the cored sediment interval. Minor cation elements, including Li, B, Sr, and Mn, exhibit elevated concentrations at intermediate depths, with maximum values observed between 138.67 and 210.55 mbsf. The variation of ammonium (NH_4^+), from 26.61 to 783.32 µM, follows alkalinity changes with depth, with a sharp increase to a maximum concentration from seafloor to 26.17 mbsf and a gradual decline to a minimum at the bottom of the hole. Phosphate decreases slightly with depth, with the highest value of 8.85 µM at 5.19 mbsf.

The percentage of calcium carbonates ($CaCO_3$) in bulk sediments varies from 16.3 to 28.4 wt% for Hole U1616A and from 1.7 to 84.5 wt% for Hole U1616B. While the lower $CaCO_3$ percentages occur in layers associated with volcaniclastic materials, higher $CaCO_3$ percentages are associated with foraminifera- and/or nannofossil-rich layers, dolomites, and the fine-grained consolidated breccia. Higher total nitrogen (TN) contents are found in total organic carbon (TOC)-rich sediments such as nannofossil ooze, nannofossil chalk, and sapropel, as confirmed by a strong positive correlation between these two parameters. Most of the sediments are characterized by atomic TOC/TN ratios lower than 9, indicating higher inputs of marine derived organic matter and/or the presence of inorganic nitrogen bound to surface mineral particles. The highest total sulfur (TS) contents (1.2–6.7 wt%) generally occur in TOC-rich layers.

The 38 headspace gas samples measured at Site U1616 (7 for Hole U1616A, 24 for Hole U1616B, and 7 for Hole U1616E) contain only methane with a concentration varying from undetectable to 2.03 ppmv.

Portable X-ray fluorescence spectrometer (pXRF) measurements were made on IW squeeze cakes and corresponding intervals along the archive section halves for Holes U1616A and U1616B. Trends in sediment geochemical data reflect compositional changes between volcanoclastic-rich layers and dolomite-rich nannofossil layers. Fe, Al_2O_3, K_2O, Rb, and Ni are all more abundant in volcanoclastic layers, while CaO and Sr are more abundant in nannofossil-rich layers. One interval of volcaniclastic-rich gravel was selected for analysis via inductively coupled plasma–atomic emission spectrometry (ICP-AES). It shows high alkali contents up to 11.6 wt% Na_2O + K_2O, because of the contribution of volcaniclastic materials.

Igneous Geochemistry

Igneous rocks collected from Hole U1616E were analyzed with pXRF, ICP-AES, and X-ray diffraction (XRD). Carbonated peridotite intervals were also analyzed for total carbon (TC), total inorganic carbon (TIC), and TS.

pXRF was used extensively at Hole U1616E to assist petrologists in characterizing and describing minor lithologies and veins. Analyses of intervals with high concentrations of SiO_2 and/or MgO yield analytical totals >100 wt% after data correction. This overestimation of SiO_2 and MgO stems from the pXRF's internal calibration, which seems to be dependent on the relative abundance of these two oxides. Due to these data issues, pXRF data was used only qualitatively for assistance with petrographic description.

Results of ICP-AES analyses on the peridotites confirmed that there is much less chemical heterogeneity between the peridotites from Hole U1616E compared to those from Hole U1614C. However, like at Hole U1614C, the peridotites from Hole U1616E show CaO abundances higher than expected for a general mantle melting trend. This finding prompted us to analyze the peridotites via XRD, and for TC and TIC, which confirmed the presence of calcium carbonates and the direct linear relationship between calcium carbonate content and CaO content measured with ICP-AES. Therefore, we can confirm that the exceptionally high CaO content of peridotites is imparted by the carbonation processes.

Physical Properties

Site U1616 comprised three holes: Hole U1616A, which sampled the first 50 m of sedimentary cover; Hole U1616B, which was cored from ~31 mbsf to the upper part of the consolidated breccia; and Hole U1616E, which cored the breccia and underlying basement rocks. Standard physical properties measurements, including gamma ray attenuation (GRA) bulk density, *P*-wave velocity (V_P), and magnetic susceptibility (MS) measured on the Whole-Round Multisensor Logger, in addition to natural gamma radiation (NGR) were performed on whole-round core sections of both sediment and hard rock. Section halves were X-ray imaged, and discrete V_P measurements and thermal conductivity measurements were also made on intervals along the section halves. Moisture and density (MAD) samples were collected as cylinders or wedges from the cored material.

In Hole U1616B, GRA bulk density is variable in Cores U1616B-2H through 6H, then gradually increases with depth from Core 10X. MS values are high in the uppermost cores where the concentration of volcaniclastic material is relatively high, then show spikes in MS downhole, likely corresponding to volcaniclastic layers. NGR has intermediate values through most of the hole, peaking in Cores 19X and 20X around the occurrence of the tuff. NGR is low through the rest of the hole. Thermal conductivity shows a clear increasing trend with depth.

The basement at Hole U1616E contains predominantly serpentinized peridotite with intrusions of varying lithologies. MAD densities range from 2.3 to 2.99 g/cm^3 in a gabbro, while serpentinized peridotites average 2.59 g/cm^3. Porosity ranges from 1% (gabbro) to 21% (diorite) and average ~8.1%. Discrete V_P measurements range from 2548 (serpentinized peridotites) to 6024 m/s (gabbro) and have an average value of ~3778 m/s. Finally, thermal conductivity varies from 2.12 up to 3.79 W/(m·K) within a consolidated breccia. NGR data has an average value of 5.9 counts/s, while MS has an average value of 697 IU and peak value of 5000 IU in the lowest unit.

Downhole Measurements

The APCT-3 tool was deployed at Site U1616 during coring of Cores U1616A-4H and U1616B-4H. Combined with measurements of seafloor water temperature, these two formation measurements give a thermal gradient of 8.8°C/100 m, hence a heat flow estimate of 79 mW/m^2, an even lower heat flow value than that measured at Site U1615.

Two logging attempts were made in Hole U1616E during our initial drilling in the hole with the triple combo tool string, including MS, electrical resistivity, bulk density, and NGR tools. During the first logging attempt, an obstruction was encountered just below the breccia/basement contact at 306.7 mbsf. The Magnetic Susceptibility Sonde and the bottom of the tool string recorded data down to this depth, going through the brecciated basement top and 1 m into peridotites. Electrical resistivity, bulk density, and NGR data were also recorded over a shorter distance. On the second run, the tool string became stuck inside of the pipe and logging operations were ended to clear the obstruction. For both runs, the NGR tool recorded data through pipe up to the mud line. The seafloor temperature was measured as 13.40°C. In all, 42 m of petrophysical data were recorded in the open hole at Hole U1616E.

Logging was also attempted in Hole U1616E after we had finished coring the hole to its total depth of 427.2 mbsf. We hoped that the continued operations and additional cleaning of the hole would increase the chances of successful logging; however, the bottom of the triple combo tool string passed only ~25 m out of the logging bit, reaching a depth of 342.0 mbsf in the open hole, before an obstruction was encountered. Processing of the limited logging data from Hole U1616E is still in progress.

Microbiology

At Site U1616, whole-round samples and syringe plugs of the core were collected on the catwalk for viral metagenomics, 16S rRNA, microbial experiments, and viral counts. Viral metagenomics and 16S rRNA samples were double-bagged and frozen at –86°C immediately after collection. Samples for viral counts were fixed in a phosphate-buffered saline-formaldehyde solution. Microbial experiments were initiated under anaerobic conditions for a sample from Section U1616A-11X-2. A viral incubation experiment was initiated for a sample from Section U1616E-2R-2.

Oxygen measurements were conducted on whole-round cores from Hole U1616A immediately after core recovery and prior to temperature equilibration, by drilling two small holes in the core liner and inserting the oxygen and temperature probes into the undisturbed core center. In Core U1616A-1H, oxygen was detected in the first 0.6 m of Section 1H-2, with the lowest detectable value of 0.6 μM. Thereafter, readings were maintained at very low concentrations until 179 mbsf where there was an increase in concentration. However, only one additional measurement could be made below this depth because the compacted sediments inhibited probe insertion.

Additional samples were taken for microbial contamination analysis using PFD tracer. These were taken each time microbiology samples were collected. Three samples, including drilling fluid, core exterior, and core interior were extracted using syringes and placed in glass vials. They were analyzed in the laboratory using a gas chromatograph. Comparison between core exterior and interior samples demonstrates successful delivery of the tracer to the core exterior and very low penetration of PFD into the core interiors, except for the sample from Section U1616B-21X-5 which was identified as contaminated. The average concentration of the PFD in interior samples was 0.28 ng/g.