IODP Expedition 402: Tyrrhenian Continent–Ocean Transition

Site U1614 Summary

Background and Objectives

Site U1614 (proposed Site TYR-11A) is one of four drill sites in the Vavilov Basin that target exhumed mantle peridotites. Site U1614 is near the center of the planned north–south transect across the Vavilov Basin and is located on the flank of a basement high, interpreted to be the uplifted footwall of a long-offset low-angle detachment fault that exhumed the mantle. As for the other sites in the Vavilov Basin, the scientific objectives of Site U1614 are (1) to date with biostratigraphy and magnetostratigraphy the oldest sediment above the basement contact to constrain the timing of mantle exhumation, (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.

The original Site U1614 drilling plan was modified after the bottom-hole assembly (BHA) became irremediably stuck in the previously drilled Hole U1612A (located in the Vavilov Basin approximately 10 km southwest of Site U1614), likely due to material falling into the hole from thick intervals of unconsolidated volcaniclastic sediments in the upper part of the sediment column. The modified drilling plan was to first drill a hole with the advanced piston corer/extended core barrel (APC/XCB) system to sample the sediments, tag the basement (expected at ~200 meters below seafloor [mbsf]), and determine the vertical extent of unstable volcaniclastics that could cause drilling problems. We would then install casing over these problematic intervals in a second hole, to be cored with the rotary core barrel (RCB) system to at least 140 m into a basement that is expected to consist of exhumed mantle peridotite. After coring, we planned to run downhole logging to supplement core recovery and assist the interpretation of the drilled basement interval.

Operations

The 80.4 nmi transit to Site U1614 from Site U1613 on the Cornaglia Terrace took 7.6 h at an average speed of 10.6 kt. We arrived on site and transitioned to dynamic positioning (DP) mode at 1755 h (UTC + 1 h) on 23 February 2024. The precision depth recorder estimated the seafloor as 3580.1 meters below sea level (mbsl). An APC/XCB BHA with a 9⅞ inch polycrystalline diamond compact bit was assembled and deployed to 5 m above seafloor. Prior to spudding, we pumped enough microbial contamination tracer with circulating drilling fluid to fill the drill string.

Hole U1614A was spudded at 0645 h on 24 February, with the first core recovering 5.7 m of sediment as well as the mudline. Based on this recovery, the seafloor is calculated at 3579.0 mbsl. Cores U1614A-1H through 9H were full-length APC cores that advanced 77.3 m and recovered 76.21 m of sediment (98%). Measurements with the third-generation advanced piston corer temperature (APCT-3) tool were made during Cores U1614A-4H and 7H, and all full-length APC cores were oriented. Cores 7H and 9H were partial strokes, where Core 9H experienced 30,000 lb of overpull. As a result, Cores 10F–14F were taken using the half-length APC (HLAPC). These cores advanced 16.4 m to a total depth of 93.7 mbsf and recovered 12.72 m of sediment (78%). Gravel recovered in the tops of multiple cores is interpreted as fall-in.

Cores U1614A-15X through 34X advanced 186.4 m to a total depth of 280.1 mbsf and recovered 90.41 m of core material (49%). Recovery across this interval ranged from 0% to 103%. The basement contact was encountered in Core 33X. Core 34X penetrated another 9.8 m but only recovered 0.76 m (8%). We attempted to XCB drill an additional core, but experienced high torque after deploying the core barrel. We recovered a ghost core, Core 35G, which contained 2.16 m of fill from an undetermined depth, and then we ended the hole. Pipe was tripped back to the surface and the drill collars were racked. We then laid out the upper guide horn to prepare for a jet-in test for the planned casing installation at this site. In total, the 35 cores collected in Hole U1614A recovered 179.36 m of material, or 64%, and took 3.2 d.

The planned casing installation consisted of a 13⅜ inch casing string to ~60 mbsf and a second 10¾ inch casing string extending to ~40 m above the basement interface. A jet-in test in Hole U1614B was necessary to determine if the full 60 m length of the 13⅜ inch casing string could be installed. We made up the BHA with a 14¾ inch tricone bit, tripped pipe to the seafloor, and spudded Hole U1614B at 0900 h on 27 February. The jet-in test was successful, penetrating 65.2 mbsf. We then pulled out of the hole and tripped back to the surface, with the bit clearing the rig floor, ending Hole U1614B.

The reentry cone was then positioned in the moonpool and the five joints of 13⅜ inch casing, as well as a shoe joint, were hung in the guide base, using a 16 inch casing hanger and a 16 to 13⅜ inch crossover. The stinger with the running tool and BHA were made up and latched into the casing and reentry cone, which was deployed through the moonpool at 0515 h on 28 February. Pipe was tripped toward the seafloor and the vibration isolated television (VIT) camera system was deployed after 60 stands of pipe, to follow the reentry cone. At 1400 h, we installed the top drive and spudded Hole U1614C, jetting in casing to a depth of 66.0 mbsf. We detached the running tool from the casing at 1550 h by rotating the drill string 3½ times to the right, began pulling out of the hole, and recovered the VIT. We then tripped pipe back toward the surface.

To aid installation of the 10¾ inch casing string, we conducted a drill ahead to a depth ~20 m above the expected basement contact. The drilling BHA with a 12¼ inch bit was made up and deployed, reentering Hole U1614C at 1100 h on 29 February using the VIT camera system to guide reentry. After retrieving the VIT, the drill ahead successfully penetrated to a depth of 250.0 mbsf, after which the hole was displaced with 100 bbl of heavy mud, and pipe was tripped back to the surface.

The Conductivity-Temperature-Depth sensor and the Niskin bottle water sampler were attached to the VIT camera system frame and deployed during the first two runs of the VIT, generating temperature and conductivity profiles of the water column and collecting bottom seawater samples for chemistry and microbiology.

The final casing step involved the installation of the 10¾ inch casing string. The running tool and drill collars were made up and a standard cut and slip of drill line was performed prior to running the 20 joints of casing. With the casing hanging off the moonpool doors, we made up the BHA and latched into the casing hanger, and then began tripping toward the seafloor. The VIT camera system was launched and lowered to guide reentry. The second reentry into Hole U1614C occurred at 0030 h on 2 March. We washed in the casing to a depth of 227.3 mbsf, working through an obstruction at 172.7 mbsf by picking up the top drive and using the rig pumps. The casing was latched and released at 0345 h. We recovered the VIT camera system and tripped pipe back to the surface, with the bit clearing the rig floor at 1300 h. After racking the drill collars in the derrick and reinstalling the upper guide horn, we prepped the RCB core barrels and made up the BHA with a C7 RCB drill bit for coring basement in Hole U1614C.

The third reentry into Hole U1614C to begin RCB drilling occurred at 0135 h on 3 March, guided by the VIT camera system. We then picked up the top drive, recovered the VIT, and dropped a core barrel with the bit at a depth of 229.7 mbsf. The core barrel was washed down to the bottom of the previous drilled interval (250.0 mbsf) before we began coring.

Cores U1614C-2R through 28R advanced 160.6 m to a total hole depth of 410.6 mbsf with a 71.58 m recovery (45%). Recovery varied from 6%–99%. Cores from 8R–28R were taken as half advances to improve recovery. After drilling Core 11R, we experienced high overpull and loss of rotation, but we were able to work the pipe free. Recovery was relatively high (61%) in Cores 5R–19R, as well as in Cores 22R–28R (49%), and was very low in Cores 20R (9%) and 21R (21%), likely due to the differences in lithology recovered.

Following recovery of Core U1614C-28R, we lost pipe rotation and became stuck. Working the pipe allowed us to regain rotation and lay out two single pieces of pipe from the drill string. The drill string became stuck again, with no rotation or vertical movement. Good circulation suggested that we were losing circulating fluids into the formation. From 1430 to 1700 h on 6 March, we worked the pipe without regaining movement. The vessel was offset to retrieve the core barrel and release the bit as a last attempt to free ourselves. When this effort failed, we made the decision to deploy a severing charge and sever the pipe just below the depth of the casing string. A severing charge was lowered to 234.7 mbsf on the Schlumberger wireline. The charges were detonated with 20,000 lb overpull on the pipe; an immediate drop in string weight indicated that we were free. The Schlumberger wireline was recovered, and we began pulling out of the hole. Once the end of the pipe cleared seafloor at 0500 h on 7 March, the vessel started to move in DP mode at 0.5 kt toward proposed Site TYR-16A (Site U1615). The end of the pipe reached the rig floor at 1000 h, ending Hole U1614C and Site U1614.

Principal Results

Lithostratigraphy

Three primary units were defined for the sediments from Hole U1614A. The first unit was split into three subunits based on the abundance of volcaniclastic gravel. Unit IA is nannofossil-rich mud with intervals that are more sand-rich or silt-rich. The subunit has small, frequent turbidity deposits with erosive bases and fining upward sequences. Unit IB contains almost entirely volcaniclastic gravel. Drilling disturbance makes it difficult to pick out any sedimentary or structural features. Unit IC also contains some volcaniclastic gravel, but its consistent appearance in the tops of cores suggests that it is fall-in from the overlying subunit IB. The rest of subunit IC is composed of sandy silt and silt.

Unit II is split into two subunits. Unit IIA consists of volcaniclastic material in the form of unconsolidated volcaniclastic breccia with a more consolidated tuff found downcore. Foraminifera-nannofossil-rich silt is observed in between the breccia and the tuff; this lithology shows extensive drilling disturbance in the form of biscuiting. Unit IIB is made up of nannofossil chalk with minor volcaniclastic components. Glauconite-rich and sapropel layers are present as well as pyrite nodules and fragments. Unit III is made up of reddish dolomitic muds and nannofossil chalk overlying the basement contact. The interface is denoted by dolomite overlying a thin layer of greenish gray nannofossil chalk that directly contacts the serpentinite.

Biostratigraphy

Micropaleontologists obtained and analyzed 32 core catcher (CC) samples from Hole U1614A for biostratigraphic analysis. Most CC samples are volcanoclastic in nature and barren of any planktic foraminifera. When present, planktic foraminifera from the middle (between Samples U1614A-9H-CC and 23X-CC) and the bottommost (Samples 29X-CC to 33X-CC) volcanoclastic-dominant layers are reworked, making biozonal and age assignments difficult. The topmost Holocene sedimentary layers (Samples 1H-CC to 3H-CC) have well-preserved planktic foraminifera species. Additional samples were taken from nannofossil ooze intervals to refine the biozone assignments through successive sedimentary layers. Based on the planktic foraminifera assemblage found, sedimentary successions are observed to be continuous. Sample U1614A-29X-2W, 52–54 cm, the bottommost sedimentary layer to be associated with a biozone, was determined to be Early Pleistocene (late Gelasian; ≤1.95 Ma) in age.

Calcareous nannofossils were analyzed in ~30 samples in Hole U1614A. The uppermost part of this site down to Sample U1614A-12R-CC (about 100 mbsf) is represented by a nearly continuous succession ranging from Holocene to early Calabrian (biozones MNQ21 to MNQ19b), with an average sedimentation rate of ~62 m/My. In the middle of the cored interval at this site, Samples U1614A-16R-CC to 21R-CC, the succession is partially repeated and ranges from Chibanian to early Calabrian (biozones MNQ19d to MNQ19a). The calculated average sedimentation rate is ~32 m/My, with a probable hiatus corresponding to biozone MNQ19b, about 0.36 My in duration. The interval containing Samples U1614A-22R-CC to 28R-CC ranges from Calabrian to late Gelasian (biozones MNQ19b to MNQ18), with an average sedimentation rate of ~84 m/My. Samples U1614A-31R-CC to 33R-1W-124 cm, just above the basement, were assigned to biozone MNQ19a of Calabrian age. The repeated intervals may be due to the presence of slumps, folds, or reverse faults.

RCB drilling in Hole U1614C captured the sediment/basement interface, including ~20 m of sediment overlying the contact. Two CC samples and two additional toothpick samples from the core sections were analyzed to estimate the age of the sediments deposited above the basement. Sediments from three of the four samples were found to be volcanogenic in nature and were completely devoid of any planktic foraminifera; thus, the deepest sample to which an age could successfully be assigned was Sample 402-U1614C-3R-CC, from the bottommost core above basement. Both foraminifera and nannofossil data show this sample to be late Gelasian (1.95–1.71 Ma) in age.

Paleomagnetism

Paleomagnetic measurements were performed for the sediments and a small portion of basement recovered in Hole U1614A, as well as the basement recovered over the

~150 m drilled interval in Hole U1614C. Demagnetization of natural remanent magnetization (NRM) of the archive-half sections of sediments up to 20 mT peak alternating field (AF) showed that the cores recorded normal polarity almost exclusively, except for a few highly disturbed sections and cores (34.2–53.2 mbsf), although the biostratigraphy suggests that the time span of the sedimentary column should include multiple reversed polarities. Characteristic remanent magnetization determined from discrete samples shows only one NRM component in the range between 15 and 80 mT.

For the serpentinized peridotites found in Hole U1614C, initial NRM is strong with a normal polarity. However, the intensity drops quickly at low demagnetization levels. Once the overprint is removed via demagnetization at 20 mT peak AF, most rock segments exhibit a reversed polarity. Different magnetic minerals, including magnetite, hematite, and possibly iron sulfide, were found through experiments on the discrete samples.

Igneous and Metamorphic Petrology

Basement cores from Site U1614 consist of very heterogeneous mantle lithologies, including serpentinized lherzolites, harzburgite, dunite, and pyroxenite, with a short interval of brecciated ophicarbonate. The mantle section is crosscut by mafic intrusions. The recovered cores of the basement show variable degrees in the style of deformation and alteration. The degree of alteration is moderate to high. Alteration minerals include serpentine, magnetite, clays, and carbonate with instances of tremolite and amphibole replacing the clinopyroxene. The primary mineralogy and alteration features were also confirmed by thin section observations.

Five lithological units were defined in basement based on primary igneous and alteration features. Units I–III are sediment lithological units. Unit IV includes the sediment/basement interface and contains a mélange of mud and serpentinized peridotite. Unit V consists of variable mantle lithologies with gabbroic intrusions; Unit VA is lherzolite-dominated, transitioning to dunite- and harzburgite-dominated in Unit VB. Unit VI is defined by plagioclase- and clinopyroxene-bearing peridotites with dense mafic veins increasing in concentration with depth. Unit VII contains reddish serpentinized peridotites with mafic intrusions and dense veins. The lithology in Unit VIII returns to plagioclase- and clinopyroxene-bearing peridotites and is relatively homogeneous compared to overlying units.

Structural Geology

Sediment in Hole U1614A has subparallel bedding throughout the succession. Observed features include laminations, graded bedding in a turbidite layer in Core U1614A-26X, and normal faulting with 2 mm thick boudinage in Section 26X-6.

The structural geology group described and measured the orientation of ~770 deformation structures in the 150 m of mantle peridotites recovered from Hole U1614C. They include crystal-plastic and brittle fabrics, magmatic impregnations, gabbroic intrusions, and metamorphic veins (serpentine and carbonate).

Sediment and Porewater Geochemistry

A total of 23 interstitial water (IW) samples were collected from the sedimentary succession of Hole U1614A. While pH values show little variation with depth, IW salinity generally decreases with depth except at 78.4 mbsf and 118.9–151.9 mbsf. IW alkalinity, as well as ammonium and phosphate concentrations, are characterized by greater values between 10.1 and 76.0 mbsf, probably resulting from organic matter degradation. Alkalinity decreases continuously from the seafloor until 78.18 mbsf, and is then constant with depth, whereas Ca^{2+} content becomes elevated below the approximately same depth. Mg^{2+} concentrations decrease consistently with depth in the upper ~200 mbsf. The sulfate concentration also shows a decreasing trend for almost the entire cored interval. The concentration of minor elements (Li, B, and Sr) increases gradually below 78.18 mbsf. In particular, the ratio of B/Cl at the base of the hole is 5× the normal seawater value, suggesting the availability of organic matter is contributing to the concentration of B.

The percentage of calcium carbonate ($CaCO_3$) varies between 0.4 and 77.8 wt%. Total carbonate ranges from 5.7 to 77.9 wt% and is always higher than the percentage of $CaCO_3$, indicating the occurrence of other carbonates in the sedimentary column. A positive correlation is observed between the percentages of $CaCO_3$ and the total carbonate contents. The percentage of sedimentary organic matter varies between 3.1 and 17.3 wt%, as determined by loss on ignition (LOI). This percentage is higher than 14.7 wt% at 23.2, 85.8, 140.6, and 228.1 mbsf. Low total organic carbon (TOC; from below the detection limit to 0.65 wt%) and total nitrogen (TN; from 0.004 to 0.21 wt%) contents are measured for sediments collected from this site. Most of the sediment samples show a TOC/TN ratio less than 12, indicating that sedimentary organic matter primarily originates from a marine source, except at 29.1 and 222.6 mbsf. However, the occurrence of inorganic nitrogen could result in an overestimation of the relative contribution of a marine source. Total sulfur generally varies between undetectable and 0.27 wt%, except at 222.6 mbsf where it reaches 2.36 wt%.

Headspace samples were taken from each core to monitor C_1-C_6 hydrocarbons, according to the standard safety protocol during drilling. At Hole U1614A, 32 headspaces were analyzed. Only methane (CH_4) is identified with concentrations ranging from 0.1 to 49.6 ppmv.

Igneous Geochemistry

The geochemistry of basement rocks from Hole U1614C was examined via portable X-ray fluorescence spectrometer (pXRF; 85 intervals analyzed), LOI, and inductively coupled plasma–atomic emission spectroscopy (ICP-AES; 26 discrete samples analyzed).

Intervals for pXRF analysis were chosen in collaboration with the igneous and metamorphic petrologists to assist with core descriptions and to acquire preliminary geochemical data. These data confirm the wide range of lithologies recovered in Hole U1614C, including various types of peroditite, websterite, and granitic rocks. Peridotites are generally high in Cr, as expected for mantle lithologies. Seemingly sporadic increases in TiO_2 occur in some dunites and gabbros; these increases will be better quantified and investigated via ICP-AES.

Physical Properties

Core material was recovered from two holes at Site U1614: Hole U1614A, which captured the sedimentary succession, and Hole U1416C, where the installation of casing and a reentry cone allowed RCB drilling of ~150 m of basement. The physical properties group performed regular measurements, including gamma ray attenuation bulk density, *P*-wave velocity (V_P), and magnetic susceptibility on the Whole-Round Multisensor Logger (WRMSL), and natural gamma radiation (NGR) on more than 250 m of cores from both holes. X-ray images were generated for all section halves. In addition, 50 and 55 moisture and density samples were collected and analyzed from Holes U1614A and U1614C, respectively. Finally, the group performed 62 discrete V_P measurements with the Gantry system on sediment from Hole U1614A. The Gantry system was used to make 644 V_P measurements on section halves from Hole U1614C as the hard rocks did not fill the core liner, eliminating use of the WRMSL as an option for measurements of V_P.

Sediment recovered in Hole U1614A varies from highly porous (~70% porosity; density ~1.3 g/cm^3) unconsolidated clays to denser and sometimes consolidated volcaniclastic tuffs with a density up to 2.64 g/cm^3 and porosity of 37%. Seismic velocity ranges from 1.48 km/s for mud to 2.5 km/s in tuff, while thermal conductivity is 0.655 to 1.657 W/(m·K) with a low value recorded over the tuff interval. Notably, each lithostratigraphic unit has characteristic K, Th, and U contents, with Unit IIB (Cores U1614A-29X to 32X) showing very high NGR values up to 400 counts/s. The basement rocks (primarily peridotites) from Hole U1614C have densities of ~2.5 g/cm^3 with porosities ranging from 2% to 19% and seismic velocities in the range from 2.4 to over 6 km/s. NGR is generally low, except for in Cores U1614C-20R and 21R; however, low recovery makes this interval difficult to interpret.

Downhole Measurements

In Hole U1614A, the APCT-3 tool was deployed at 34.2 and 62.7 mbsf (Cores U1614A-4H and 7H) and collected readings of 20.43° and 27.42°C, respectively. When combined with the seafloor temperature of 13.65°C recorded after the second APCT-3 run, it yields a thermal gradient of 17.9°C/100 m and a heat flow of 161 mW/m^2 using a thermal conductivity of 0.9 W/(m·K).

Planned logging for Hole U1614C could not be accomplished after the drill pipe was severed and the hole was lost.

Microbiology

In Hole U1614A, whole-round samples and syringe plugs of core were collected on the catwalk for metagenomics, 16S rRNA, microbial experiments, and viral counts. Metagenomic and 16S rRNA samples were frozen at –86°C immediately after collection. Samples for viral counts were fixed in phosphate-buffered saline-formaldehyde solution. Microbial experiments were initiated in anaerobic conditions, including enrichment cultures, viral incubations, and prophage induction experiments for Sample U1614A-2H-5, 137–142 cm.

Pore water dissolved oxygen measurements were made on whole-round core sections from Hole U1614A, 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. Oxygen is detected in the upper 20 cm of Section U1614A-1H-1, with a maximum concentration of 109.5 μM, and decreases with depth. Measurements continued through the base of Section 3H-5, although most had undetectable levels of oxygen. Measurements were attempted on Cores 4H–8H; however, as these cores are very sandy and a good contact with the probe tip could not be achieved, the measurements were of poor quality. As sand can also damage the fiberoptic probes, it was not feasible to proceed with oxygen measurements. A marginal increase in oxygen in Core 8H was observed, but it was associated with a possible void space in the section.

During APC/XCB coring, the microbial contamination tracer perfluorodecalin was pumped with drilling fluid. Samples to evaluate the extent of core contamination were taken each time a microbiology sample was collected. Three samples, including drilling fluid, core exterior, and core interior, were extracted using syringes and placed in glass vials. They were then taken to the laboratory and analyzed on the gas chromatograph (GC). The results were compared between the drilling fluid and the core samples (inner and outer). Most of them were unaffected by drilling fluid intrusion, as the GC detected minute amounts that could be interpreted as clean samples. However, two of the samples showed high tracer peaks, indicating drilling fluid intrusion (samples from Sections 1H-4 and 17X-4).

The Niskin bottle water sampler deployed on the VIT camera system frame collected 1 L of water from approximately 3550 mbsl. This sample was processed in the laboratory, with 5 mL distributed in 1 mL cryotubes and fixed with 4% formaldehyde for cell counts. The remaining water was filtered onto a 0.2 µm polycarbonate membrane filter, and the entire filter was then wrapped in an aluminum envelope and frozen at –86°C.