IODP Expedition 402: Tyrrhenian Continent–Ocean Transition

Site U1617 Summary

Background and Objectives

Site U1617 (proposed Site TYR-02A) is located on the Campania Terrace at the western end of the planned west–east transect across the Tyrrhenian Sea, on the lower continental slope of the Tyrrhenian margin of peninsular Italy. The basement in this margin has been proposed to be extended continental crust based on subdued magnetic anomalies and extensive outcrops of continental basement rocks sampled by dredging. An alternative hypothesis is that the crust of the Campania Terrace is oceanic because of its seismic velocity structure. The scientific objectives of Site U1617 were (1) to recover a sequence of hemipelagic Pliocene–Pleistocene sediments and, possibly, of Messinian evaporites; (2) to establish the age of the sediment/basement interface using tephrachronology, biostratigraphy, and magnetostratigraphy; and finally, (3) to determine whether the basement is rifted continental material or basalt formed by magmatic accretion.

The original plan for Site U1617 was to drill a single hole with the rotary core barrel (RCB) coring system through the total sediment column that was expected to be about 460 m thick and sample an additional 70 m of basement rocks. After coring, downhole geophysical logging was planned in the same hole to complement core recovery and to collect in situ measurements of formation physical properties. This original plan was modified after the loss of two RCB bottom-hole assemblies (BHA) in Holes U1612A and U1614A, which left us with only one remaining crossover drill collar to build a RCB BHA. As we intended to core at least another RCB hole in the Vavilov Basin after the Campania Terrace site, we decided not to use the RCB system at Site U1617 to avoid any possibility of losing the last RCB BHA available in the expedition. During Ocean Drilling Program (ODP) Leg 107, the drill string became stuck in Hole 654A (Upper Sardinia margin) while drilling through an unstable conglomerate layer beneath Messinian evaporites and could be freed only after 3.5 h of strenuous efforts. Trying to reach the basement below the Messinian at Site U1617 may pose the same risk. The drilling plan at Site U1617 was therefore modified to core a single hole using the advanced piston corer/extended core barrel (APC/XCB) system, going as deep as possible through the Messinian deposits and possibly reaching the basement. Drilling operations would be stopped if problems were encountered or when drilling rates became too slow or resulted in poor recovery. After coring, the hole would be logged as in the original plan.

Operations

The 40.1 nmi transit from Site U1616 to Site U1617 was completed at an average speed of 10.4 kt, with the vessel arriving at 2150 h on 12 March 2024 and transitioning from cruise to dynamic positioning (DP) mode. The precision depth recorder gave a water depth reading of 2822.3 m. After tripping pipe to the seafloor, we spaced out and spudded Hole U1617A at 0715 h on 13 March, confirming a water depth of 2822.3 m. The mudline Core U1617A-1H advanced 4.5 m with 100% recovery. Coring continued smoothly up until Cores 15H, 16H, 20H, and 21H, which were partial strokes, and the drill bit was advanced by recovery. Cores 22F–27F were subsequently collected as half-length APC (HLAPC) cores. Cores 16H–27F all experienced overpull, ranging from 12,000 to 40,000 lb. As such, the XCB system was used starting with Core 28X. Recovery in Cores 28X and 30X–35X was over 100%, but Cores 29X, 36X, and 37X had low recovery. Rate of penetration (ROP) slowed considerably starting in Core 36X, and a lithological change into evaporite deposits was noted. All cores after Core 36X were taken as half advances to improve recovery and because of slow ROP. Coring continued through Core 47X, reaching a final hole depth of 339.9 mbsf. While we did not achieve the objective of tagging basement, the hole was ended to conserve time and because the thickness of the evaporite deposits from the seismic data was not clear.

Overall, Hole U1617A recovered 304.2 m of sediment from the 339.9 m advance (89%). APC and HLAPC cores recovered 217.74 m of sediment (104%) while XCB recovered 86.42 m (66%). Advanced piston corer temperature (APCT-3) tool measurements were made during Cores U1617A-4H, 7H, and 10H. Nonmagnetic core barrels were used for all APC cores, and all full-length APC cores were oriented. The perfluorocarbon microbial contamination tracer was pumped with the drill fluid throughout.

Following completion of coring in Hole U1617A, the hole was conditioned for downhole logging via pumping a sweep of high viscosity mud. The drill pipe was tripped up with the bit at a depth of 74.6 mbsf and the triple combo tool string deployed to log the open hole. At 0500 h on 16 March, with the triple combo tool string at a depth of 135.4 mbsf, the tool string encountered an obstruction and this first logging attempt was ended. The tools were recovered and three stands of drill pipe were added to the drill string, bringing the bit depth to 151.7 mbsf, past the initial obstruction. At 0845 h, the triple combo tool string was deployed a second time; however, the tool string encountered an obstruction just outside of the bit and was unable to completely exit the drill pipe. The decision was made to end logging attempts and pull out of the hole. At 2100 h, the rig floor was secured, the thrusters were raised, and we began the transit back to Site U1616 where we plan to install a reentry system and casing for RCB drilling in basement.

Operations at Site U1616 occupied 17–27 March. After encountering a formation that caused high torque and overpull while coring in Hole U1616E, and after attempting to log the hole, the decision was made to return to Site U1617 and drill a second hole that would penetrate past the Messinian deposits into pre-Messinian sediment and/or basement. Due to the poor recovery with the XCB system in Hole U1617A, the plan was to drill ahead to 250 mbsf with an RCB bit and then core with the RCB system until we had at least captured the sediment/basement interface. The return transit from Site U1616 to U1617 included surveying with the 3.5 and 12.0 kHz sonar systems, crossing perpendicular to a series of ridges that may have formed during the detachment faulting. In all, the transit was 57.7 nmi and took 5.3 h at a speed of 10.9 kt.

After the vessel arrived on site, we lowered the ship's thrusters and transitioned to DP mode. By 1600 h on 27 March, we were positioned over the coordinates for Hole U1617B, which was offset ~20 m north of Hole U1617A. We made up the BHA with an RCB bit and began tripping pipe toward the seafloor. Hole U1617B was spudded at 2330 h on 27 March. Drilled interval U1617B-11 in Hole U1617B penetrated to a depth of 250.0 mbsf and was completed at 1030 h on 28 March, before recovering the center bit so that coring could begin.

RCB drilling in Hole U1617B progressed from 250.0 to 370.4 mbsf with Cores U1617B-2R through 22R. Recovery was high in Cores 2R–5R (ranging from 89%–126%), but only 10% in Core 6R. Cores were drilled as half advances starting from Core 7R to improve recovery. The low recovery is attributable to the evaporite and halite lithologies. The final core, Core 22R, crossed a lithological boundary from halite into a black shale that was observed on the catwalk to have a strong petroleum smell. Coring operations were paused while the headspace gas safety measurement for hydrocarbon content and composition was completed. The sample was found to have an anomalously low ratio of methane/ethane, indicating a thermogenic origin, halting further drilling in Hole U1617B. Overall, coring in Hole U1617B advanced 120.4 m and recovered 68.6 m of sediment, evaporites, and shale (57%).

Preparations then began for logging of Hole U1617B using the triple combo and Formation MicroScanner (FMS)-sonic tool strings. Drill fluid was circulated through the hole, and the core barrel that was deployed prior to stopping coring operations was retrieved. Pipe was tripped up to a depth of 311.6 mbsf and a 40 bbl sweep of sepiolite mud was pumped. Pipe was then tripped back down to 370.4 mbsf and the rotary shifting tool was deployed to release the RCB bit at the hole bottom. Finally, the pipe was set at 279.9 mbsf and the triple combo tool string was deployed at 1700 h on 30 March. The tool string encountered an obstruction at 328.4 mbsf that could not be worked through. The triple combo tool string was recovered. Because we did not reach a great enough depth to open the caliper on the triple combo and measure the hole diameter, we could not run the FMS tool, so instead we ran the Dipole Sonic Imager (DSI) tool without the FMS. The sonic tool successfully passed down to the obstruction at 328.4 mbsf, and then completed an uplog. By 0445 h on 31 March, the tool had been recovered and rigged down.

We picked up the top drive and washed down past the obstruction to the hole bottom, then continued to circulate while pulling the pipe up to a depth of 336.8 mbsf with the goal of conducting a second logging run to total hole depth. The triple combo tool string was deployed at 1045 h on 31 March, with the caliper and density tools removed to shorten the tool string and maximize the depth of data recorded by the other tools. The triple combo tool string reached a depth of 364 mbsf, near the hole bottom at 370.4 mbsf. It was then recovered and the hole was displaced with heavy mud due to the anomalous C_1/C_2 ratio.

Pipe was tripped back to the surface and the rig floor was secured for transit at 2248 h. The vessel transitioned from DP to cruise mode and the transit to return to Site U1616 and deepen Hole U1616E began at 2305 h on 31 March, ending Site U1617.

Principal Results

Lithostratigraphy

The sediment sequence at Site U1617 was divided into three units based on lithology. Tephra, sapropel, and organic-rich mud layers intercalate the predominant nannofossil ooze in the upper part of Hole U1617A, defined as Unit I. Below, an intermediate unit formed by foraminifer-rich nannofossil ooze demarcates the boundary with underlying Messinian evaporitic facies recovered in Holes U1617A and U1617B. Mass transport deposits (MTD) were present throughout the whole sedimentary succession, most notably in Cores U1617A-4H, 7H, 8H, 10H, 15H, 27F, and 28X.

Unit I is divided into three subunits. Unit IA is characterized by nannofossil ooze that is intercalated with tephra, sapropel, and organic-rich mud layers. Unit IB is formed by the same lithologies found in Unit IA but it is devoid of tephra layers. In Unit IC, nannofossil ooze is still the principal component, intercalated with tephra layers and characterized by the increasing content of foraminifera. Unit II consists of a predominantly foraminifera-rich nannofossil ooze deposit, sometimes intercalated with layers characterized by minor foraminifera content. Unit III contains Messinian evaporite deposits and is also divided into three subunits. Subunit IIIA is formed by oxide-, dolomitic-, gypsum-, or organic-rich mud, gypsum, nannofossil-rich mud or silt, clay with dolomite, and black shale. Subunit IIIB contains anhydrite, organic-rich mud, gypsum with anhydrite, oxide-rich anhydrite, and mudstone. Subunit IIIC is characterized by halite, gypsum, and black shale.

Biostratigraphy

Expedition 402 drilled ~340 m of sediment in Hole U1617A. Sedimentary intervals retrieved were mostly nannofossil ooze, containing very well-preserved calcareous nannofossils and planktic foraminifera. In contrast to the other sites, the volcanogenic sediments at this site are very limited. Microfossil marker species' assemblages across the various sedimentary intervals were analyzed from the core catcher (CC) samples to decipher the biostratigraphic zonation scheme at the site.

Holocene–upper Zanclean (~4.11 Ma) sedimentary successions, concurrent with planktic foraminiferal biozones MPle2b–MPl3, were recognized from Samples U1617A-1H-CC to 33X-CC. A hiatus of ~0.5 Ma duration exists between Samples 13H-CC and 14H-CC, as planktic foraminiferal events corresponding to MPl6b biozone are not detected. Sedimentary successions above and below these intervals are found to be continuous. Sediments containing evaporite minerals such as gypsum are present starting with Sample 36X-CC and are interpreted to be Messinian age deposits based on previous research in and around these regions. Two CC samples, 34X-CC and 35X-CC, were taken to date the sediments above the Messinian deposits. However, these sediments contain entirely organic silt and oxide-rich mud, which are barren of planktic foraminifera marker species. Additional samples for postcruise analyses were taken from the core sections of Cores 34X and 35X to refine the age of the sediments deposited above the Messinian sediments.

Smear slide samples for nannofossil analysis were prepared from 35 CC samples. Samples from Cores U1617A-1H through 6H yield abundant and well-preserved nannofossil assemblages. These are assigned to the interval between biozone MNQ21 and subzone MNNQ19c of early Pleistocene–Holocene age (<1.24 Ma). Samples U1617A-7H-CC to 13H-CC were assigned to the biostratigraphic interval spanning the MNQ19d–MNQ19a biozones (early/middle Pleistocene), highlighting a repetition in the sedimentary succession that may relate to slumping or MTDs. None of the samples were attributed to the ~0.2 Ma long MNQ18 biozone. From Sample U1617A-13H-CC downhole, we recovered an almost continuous sedimentary succession ranging from biozone MNQ17 (early Pleistocene, Gelasian) to MNN12 (early Pliocene, Zanclean). The boundary between Zanclean and Messinian sediments was detected in Section U1617A-34X-4.

Hole U1617B was drilled to capture the complete Messinian sediment succession at the site. No CC samples were collected from the Messinian evaporite sedimentary sequences. The CC samples collected above (Samples U1617B-2R-CC to 5R-CC) are stratigraphically concurrent to the sedimentary succession observed in Samples U1617A-32R-CC to 35R-CC. Samples U1617B-2R-CC to 5R-CC are Zanclean age (<5.332 Ma), based on the identification of planktic foraminifera Zones MPl2 and MPl1 and calcareous nannofossil Zone MNN12. Additional samples for postcruise analyses and age refinement were taken from the core sections.

Paleomagnetism

Hole U1617A recovered 47 cores down to ~340 mbsf, ending in the Messinian evaporites. Analyses of archive-half sections on the superconducting rock magnetometer (SRM) show mostly normal polarity with sporadic reversals that appear too short in length/duration to be reliable. However, one reversal is recorded for almost the whole length of Section U1617A-18H-4A and can be correlated to the geomagnetic polarity timescale using biostratigraphy. Rock magnetic measurements of discrete samples show abnormal magnetic fabrics that may be attributed to gravitational slumps. Magnetic properties overall correlate with lithology. Specifically, the Messinian units have a much lower magnetization.

Hole U1617B recovered 21 cores to a depth of 370.4 mbsf. Archive half and discrete samples show normal polarity from the top of the cored interval to when evaporite deposits become predominant at ~290 mbsf. Here, the magnetic intensity is extremely low, close to the threshold that the SRM can detect. Thus, below ~290 mbsf, our inclination data are sporadic and unreliable.

Structural Geology

The primary structural features at Site U1617 are fine laminations of sediment interlayered by MTDs. Structural geology measurements include the orientation of bedding, fractures, faults, and folds. The high recovery allowed us to identify an angular unconformity at about 205 mbsf in Hole U1617A, which divides the succession into two structural domains. The first domain (from Cores U1617A-1H to 26F) is characterized by subhorizontal bedding (average dip 9°) interlayered by MTDs. The second domain is characterized by a change in bedding dip, with an average dip of 21°. Domain II also corresponds to the transition to Messinian deposits, characterized by alternation of colorful sediments with gypsum veins and evaporitic facies.

Sediment and Pore Water Geochemistry

There are 33 interstitial water (IW) and 55 sediment samples collected from Hole U1617A at depths ranging from 1.45 to 336.67 mbsf, and 7 IW and 16 sediment samples from 251.0 to 366.7 mbsf in Hole U1617B.

For IW samples, the pH value is in a narrow range of 7.3 to 7.6, while alkalinity (1.5–3.5 mg/L) exhibits an overall decreasing trend through the cored interval. Pore water salinity varies substantially, with all but one value ranging from 37.5 to 49.0. Above the boundary between lithostratigraphic Units I and II, salinity is approximately constant at 38.5. Below that depth, salinity increases continuously. However, one sample at 308.13 mbsf (Section U1617B-10R-1) has salinity of 73.5, deviating from the overall depth pattern. This elevated value is most likely due to the dissolution of underlying evaporite deposits. Accordingly, sodium (Na^+) and chloride (Cl^-) contents in that sample are also concentrated, with values of 1052.71 mM and 1169.83 mM, respectively, while the concentrations in other samples vary from 494.87 to 620.02 mM for Na^+ and 604.56 to 726.98 mM for Cl^-. Sulfate (SO_4^{2-}) shows significant changes (23.54–59.85 mM), decreasing from the sediment/water interface to 84.89 mbsf, and increasing downhole below that. The concentration of magnesium (Mg^{2+}) varies from 51.02 to 60.81 mM, a more limited range than has been observed at other sites in this expedition. Calcium (Ca), Lithium (Li), B (Boron), and Sr (Strontium) show elevated concentrations near the bottom of the hole, but different gradients, while there is a decrease in concentration downhole for potassium (K) and manganese (Mn). All major and minor elements fluctuate in concentration near the base of the cored interval. Ammonium (NH_4^+) varies from 0.10 μM near the seafloor to 503.89 μM at 252.67 mbsf. Phosphate (PO_4^{3-}), with a maximum concentration of 5.25 μM, shows fluctuations with no obvious trend downhole.

The percentage of calcium carbonates in the sediment varies from 0.3 to 75.5 wt%. Sedimentary total organic carbon (TOC) and total nitrogen (TN) contents range from nondetectable to 10.6 wt% and from nondetectable to 0.32 wt%, respectively. Atomic TOC/TN ratios vary between 0.3 and 79.1. Atomic TOC/TN ratios of ~10.4 or higher are found in sapropel and black shale layers, confirming that this ratio is affected by organic matter diagenesis due to more labile algal-derived organic matter rather than by higher inputs of terrestrial derived organic matter. Total sulfur (TS) contents range from nondetectable to 35.8 wt%, with the highest values occurring in these TOC-rich layers, indicating the formation of organic-S-molecules *via* sulfuration process that is known to protect these molecules from microbial degradation.

The 61 headspace gas samples analyzed (40 for Hole U1617A and 21 for Hole U1617B) mostly contain only methane except at 336.4 mbsf (Hole U1617A) and at 367.4 mbsf (Hole U1617B). In Hole U1617B, anomalous C_1/C_2 relationship with temperature (~60°C) is observed, and this observation resulted in the termination of coring in Hole U1617B.

Squeeze cakes generated during the extraction of IW from Holes U1617A and U1617B were analyzed via portable X-ray fluorescence spectrometry (pXRF), along with intervals from the corresponding archive section halves. Thirty-two squeeze cakes were analyzed from Hole U1617A and seven squeeze cakes from Hole U1617B. The data generated from Site U1617 comprise the cleanest pXRF dataset collected so far during Expedition 402 and show chemical changes downhole with good agreement between the IW squeeze cake and section half measurements. In the top 50 m of sediment at Hole U1617A, we see corresponding increases in Al_2O_3, CaO, and Ni, as the nannofossil oozes become richer in volcanic ash layers. Between 50 and 260 mbsf, contents for all reported elements are generally consistent. Below ~260 mbsf, we see sharp increases in Fe and Rb contents and equally sharp decreases in CaO and Sr contents, which probably results from the transition to organic- and oxide-rich silt lithologies from the oozes. These trends are observed to continue with depth in Hole U1617B. From ~275 to ~310 mbsf, we see increases in Fe, Cu, Ni, and Rb, and decreases in MnO, CaO, and Sr. Due to the texture and novelty of the sediments in the evaporite layers, IW samples were not taken and compositions for these sections were not determined by pXRF.

Physical Properties

Site U1617 was drilled on the Campania Terrace to the east of the Flavio Gioia Seamount. We acquired a regular set of physical properties on the 47 and 21 cores recovered from Holes U1617A and U1617B, respectively, that included *P*-wave velocity (V_P), gamma ray attenuation (GRA) bulk density, magnetic susceptibility (MS), and natural gamma radiation (NGR) measurements. In addition, we X-ray image scanned all section halves after the cores were split. We then collected 77 and 37 moisture and density (MAD) samples for density and porosity calculations, as well as performed 42 and 24 thermal conductivity measurements for Holes U1617A and U1617B, respectively. We made more than 250 point velocity measurements in the *x*-direction for the rocks recovered from both holes.

Our measurements show that the bulk density of sediments in Site U1617 varies from 1.343 to 2.925 g/cm^3 (average of 1.965 g/cm^3), while MAD porosity changes from 80% in the nannofossil-rich ooze at the top of the lithostratigraphic Unit I to 0% in the halite layer encountered in Unit III at the bottom of Hole U1617B (average porosity for the two holes is 46%). The discrete *P*-wave velocities measured on the half sections from both holes vary from 1496 m/s in Unit I to 5223 m/s in Unit III. Overall, densities, porosities, and velocities reveal a typical sedimentary compaction trend in lithostratigraphic Units I and II. High density, low porosity, and fast velocity values correspond to evaporite samples from the lithostratigraphic Unit III, consisting of the Messinian gypsum, anhydrite, and halite sequences.

NGR varies from 0 to 246 counts/s with an average value of 36 counts/s for both holes. In general, NGR has a decreasing trend from the seafloor to the top of Unit III, where it increases from ~20 to ~70 counts/s. Thermal conductivity is generally stable in lithostratigraphic Units I and II with an average value of 1.26 W/(m·K). In Unit III, the thermal conductivity increases dramatically up to 6.605 W/(m·K) over the evaporitic section, with the highest value measured on an anhydrite nodule from Section U1617B-12R-4. MS is highly variable in lithostratigraphic Unit I with individual peaks up to 800 IU for measurements on whole-round sections and up to 1300 IU for point measurements, while it is more stable for the lithostratigraphic Unit II (21 and 22 IU average on whole-round sections and points, respectively). MS is highly variable in lithostratigraphic Unit III with individual peaks to 1530 IU (whole-round sections) and 5689 IU (point measurements) over the oxide-rich intervals.

Downhole Measurements

In Hole U1617A, formation temperature measurements were made with the APCT-3 tool during the coring of Cores U1617A-4H, 7H, and 10H. These data give a thermal gradient of 12.8°C/100 m, and hence a heat flow estimate of 115 mW/m^2 for the Campania Terrace, a value close to that measured at Site U1613 on the Cornaglia Terrace (120 mW/m^2).

The triple combo logging tool string, including tools for measuring MS, electrical resistivity, bulk density, and NGR, was deployed twice in Hole U1617A. On the first run, the drill bit was positioned at 74.6 mbsf and the tool string encountered an obstruction at 135.4 mbsf that could not be worked through. For the second run, the drill bit was lowered to 151.7 mbsf, past the initial obstruction, but the logging tool could not fully pass out of the drill pipe. The bottommost tool on the string, measuring MS, recorded data to 171.5 mbsf. For both runs, the NGR tool recorded data through the open hole and through the pipe up to the mudline.

Logging occurred in Hole U1617B after coring operations were terminated due to the anomalously low methane/ethane ratios. The first run occurred with the triple combo tool string and the drill pipe set at 279.9 mbsf. The tool string recorded MS data down to 328 mbsf, going through the gypsum-rich layers and some anhydrite near the base of the section, before encountering an obstruction. Electrical resistivity and NGR data were also recorded over a shorter distance. On the second run, the DSI tool and the Hostile Environment Natural Gamma Ray Sonde recorded data down to the same depth as in the first run. The FMS tool was not run, as the caliper was not opened during the triple combo run and the hole diameter was unknown. The hole was then cleaned and the pipe moved down past the obstruction for a final logging attempt. MS, electrical resistivity, and NGR data were recorded through the halite deposits and down to ~365 mbsf, only a few meters off hole bottom (370.4 mbsf). Because we expect the halite interval to be washed out, the sonic tool was not deployed.

Microbiology

In Hole U1617A, 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 samples from Sections U1617A-9H-5 and 12H-7. In addition, viral incubations and prophage induction experiments were initiated for samples from Sections U1617A-3H-5 and 7H-5.

Oxygen measurements were conducted on whole-round cores from Hole U1617A immediately after core recovery. In Core U1617A-1H, oxygen was detected in the first 6 m, with the lowest detected concentration of 0.1 μM. Thereafter, readings were maintained at very low concentrations until 90 mbsf, where probe insertion was no longer possible because of the compacted nature of the sediment.

During coring in Hole U1617A, the microbial contamination tracer perfluorodecalin (PFD) was pumped along with drill fluid. Samples for the PFD tracer were taken each time microbiology samples were collected. Three samples from each core, including drilling fluid, core exterior, and core interior, were extracted using syringes and placed in glass vials. They were measured in the laboratory using a gas chromatograph, with results compared between exterior and interior samples. PFD was detected in core exterior samples, indicating successful delivery of the tracer, and 6 out of 27 core interior samples (from Sections U1617A-8H-6, 9H-6, 10H-6, 15H-4, 31X-6, 32X-6). However, the concentrations detected in both types of samples were very low. Most interior samples had 0 ng PFD/g sediment.