IODP Expedition 390: South Atlantic Transect 1

Site U1557 Summary

Background and Objectives

Site U1557 is in the central South Atlantic Ocean, ~1250 km west of the Mid-Atlantic Ridge at a depth of ~5000 meters below sea level (mbsl). Site U1557 was previously occupied during engineering Expeditions 390C and 395E, during which the sediment succession and uppermost <6 m of basement were cored with the advanced piston corer/extended core barrel (APC/XCB) system (Hole U1557C), and a reentry system was installed with casing that extends into the uppermost basement in Hole U1557D. The main objectives of revisiting Site U1557 during Expedition 390 were: (1) to core up to 250 m into basement with the rotary core barrel (RCB) system in Hole U1557D to collect material that addresses the petrological, geochemical, and microbiological objectives of the South Atlantic Transect (SAT); and (2) to collect wireline geophysical logging data through the basement section.

Site U1557 is located 6.7 km east of Site U1556, and the basement at both sites is predicted to have formed at ~61.2 Ma at a half spreading rate of ~13.5 m/My. Oceanic crust at these sites is the oldest that was drilled during the SAT expeditions. The mineralogy and extent of alteration of the basement rocks at Site U1557, changes in physical properties such as porosity, and the composition of the microbial communities will be compared to the same characteristics at the other sites along the transect to investigate the development of hydrothermal circulation and the crustal aging of the upper oceanic crust formed at slow to intermediate spreading rate mid-ocean ridges. The sedimentary succession at Site U1557 is about twice as thick as at Site U1556, and contrasts between these closely spaced sites will allow exploration of the blanketing effect of different sediment thicknesses on hydrothermal circulation. Basement topography between the sites may also affect circulation.

Operations

Expeditions 390C and 395E

Site U1557 was first visited during Expedition 390C, an engineering leg with the goal of coring a single APC/XCB hole to basement for gas safety monitoring and to install a reentry system with casing through sediment to ~5 m into basement. After a missed mudline in Hole U1557A, Hole U1557B penetrated to 574.0 meters below seafloor (mbsf), contacting basement at 564.0 mbsf, with an overall recovery of 414.94 m of sediment as well as the sediment/basement interface (72%). In Hole U1557C, a jet-in test determined that we would not be able to jet in the Dril Quip reentry system and five joints of 16 inch casing, prior to drilling a 10¾ inch casing string into basement. Instead, the reentry system and 16 inch casing was drilled into Hole U1557D. The casing could not be extended during Expedition 390C due to a subsea camera system failure;

Expedition 395E returned to the site, installing casing to a depth of 571.6 mbsf with the hole reaching a depth of 576.6 mbsf.

Hole U1557D

Expedition 390 arrived at Site U1557 on 12 May 2022 after moving over from Site U1556 in dynamic positioning mode. We reentered Hole U1557D with the bottom-hole assembly for RCB coring and began operations. Core U1557D-2R was the first recovered core in this hole following the two drilled intervals. Coring continued smoothly through Core 8R; Core 9R had advanced only 1 m when we had to pull out of the hole to wait on weather. After 1.5 d of waiting on weather, we continued coring from 637.1 mbsf, with Core U1557D-10R. Core 14R was the final core for the site and advanced to 684.7 mbsf; after its recovery, we began tripping out of the hole to drop the bit on the seafloor and reenter for logging. Excluding Cores 2R, 3R, and 9R, all cores were full length. A mud sweep was pumped after every core following Core 5R. Penetration rates were <2.5 m/h throughout the hole. In total, coring in Hole U1557D during Expedition 390 advanced 109.1 m and recovered 71.28 m (65%).

After dropping the bit on the seafloor using the mechanical bit release system, we reentered the hole to log with the triple combo tool string. The string included tools for measuring formation density, resistivity, and magnetic susceptibility (MS), as well as the borehole caliper. Two upward passes covering the basement section of the hole were completed, and then the sediment section of the hole was logged through casing as the tools were pulled back to the surface. Logging tools were recovered, and we departed Site U1557 to transit to Site U1559. Operations time at Site U1557 totaled 7.6 d during Expedition 390.

Principal Results

During Expedition 390, the science party described APC/XCB cored material as well as the sediment/basement interface from Holes U1557A and U1557B, collected during Expedition 390C. Expedition 390 additionally cored 109.1 m of basement in Hole U1557D. Both sediment and basement results are summarized here.

Stratigraphic Unit Summary

The cores recovered at Site U1557 comprise two sedimentary units overlying a single basement unit, identified on the basis of macro- and microscopic visual observations combined with mineralogical analyses by X-ray diffraction, spectral color analyses, and MS data. The units are numbered from the top of the hole, with units in the sedimentary section designated by Roman numerals and basement units designated by Arabic numerals; subunits are designated with letters. The sediment/basement interface was recovered at 564.8 mbsf in Hole U1557B; installation of casing into basement in Hole U1557D prevented recovery of the interval in that hole. The interface is defined as the shallowest recovered occurrence of basalt in the hole.

Sediment

Sedimentology

The sedimentary column in Site U1557 is composed of two units: alternating silty clays and nannofossil ooze (Unit I, Eocene/Recent, thickness ~290 m), laying over nannofossil/calcareous chalk deposits (Unit II, Paleocene/Eocene, thickness ~275 m). The contact between Unit I and Unit II is marked by the first substantial (>25 m thick) deposit of siliciclastic sediments (dark brown silty clays) at the Eocene/Oligocene transition. The color of the sediment primarily reflects its lithologic characteristics. Sediments composed mainly of nannofossil ooze/chalk are generally pinkish-white or light grey, whereas silty clays range from brown/dark brown, where carbonate is absent, to reddish-brown, where the carbonate content is higher. In addition to the major lithologies (nannofossil ooze/chalk and silty clay), several minor local sedimentological features are observed, including greenish-white foraminifera-rich layers/lenses (especially at the contact between silty clays and nannofossil ooze intervals), microstructural deformation (faulting and folding), and a unique clay-bearing layer (<0.8 m thick, identified as the Paleocene/Eocene Thermal Maximum [PETM] interval) in the long sequence of nannofossil chalk of Unit II.

Biostratigraphy

The ~564.8 m thick sedimentary succession of pelagic ooze, chalk, and clay in Hole U1557B ranges in age from Pleistocene to middle Paleocene. Planktic and benthic foraminifera and calcareous nannoplankton are present in varying abundance in the oozes and chalks, but are mostly absent from the clays. Preservation and abundance of calcareous nannoplankton and planktic foraminifera are better in the Paleocene and Eocene than in the Oligocene and Neogene. Sedimentation was continuous from the early Oligocene to Pleistocene. A 12.94 m thick condensed interval or hiatus composed of dark brown pelagic clay and spanning the middle Eocene to early Oligocene occurs within Cores U1557B-29X to 31X. Below this hiatus/condensed interval, sedimentation again appears to be continuous, although there are significant gaps in core recovery and some evidence for reworking in the early Eocene. We interpret a prominent reddish-brown clay in Core U1557B-50X to represent the PETM, based on the occurrence of the calcareous nannofossil genus *Rhomboaster*, which is characteristic of the PETM interval, as well as sedimentological and physical properties data indicating a significant drop in carbonate content. These observations are strong evidence that a complete PETM section was recovered within Section U1557B-50X-3. Below this hyperthermal event, continuous sedimentation is observed through to the sediment/basement interface. Samples taken directly above basement (U1557B-63X-2W, 78–80 cm; 564.15–564.17 m core depth below seafloor-B [CSF-B]) were assigned to planktic foraminifer zone P4a (between 60.54 and 60.76 Ma) and calcareous nannofossil Zones NP5/CNP7 (between 60.76 and 61.27 Ma; Gradstein et al., 2020), both of which are in good agreement with the projected crustal age of 61 Ma at Site U1557. No samples were analyzed from the limestone-basalt breccia that characterizes the transition from pelagic sediment to basement.

Paleomagnetism

The sediment package at Site U1557 was cored in Holes U1557A and U1557B during engineering Expedition 390C, during which most cores were split, and remanence measurements were made using the superconducting rock magnetometer (SRM). The natural remanent magnetization (NRM) of core sections were measured prior to applying three alternating field (AF) steps (5, 10, and 20 mT), where the remanence was measured after each step. Measurements were made at 2 cm intervals. As the working halves of Site U1557 cores were not on board during Expedition 390, no discrete samples were taken from the majority of the sediment sequence. The sediment/basement interface cores from Hole U1557B were split and analyzed during Expedition 390, with the archive halves run on the SRM and two discrete samples collected from the interface.

Measured inclinations for Hole U1557B cluster around −52.2° and 49.8°. The inclinations for Hole U1557A are slightly shallower, but within error, than the inclination expected for this latitude for a geocentric axial dipole (GAD; ±49.1° at 30°S), while those for Hole U1557B are in excellent agreement with GAD inclination. For all sites, MS and intensity correlate well with these lithological variations—high values correspond to the silty clays while lower values correspond to the biogenic carbonates. The remanence intensities for the sediment packages at Site U1557 are relatively strong for pelagic material. Throughout Lithological Unit I and Unit II at Hole U1557B, intensity averages are on the order of 10^{-2} A/m for both the NRM and 20 mT intensity. Unit I intensities are roughly twice what they are for Unit II. Three intervals of normal polarity are identified in Core U1557A-1H that we correlate to the Brunhes, Jaramillo, and Cobb Mountain chrons, respectively. Similar normal polarity intervals are also identified in the uppermost cores of Hole U1557B. Unfortunately, the depth of the Brunhes/Matuyama chron boundary in Hole U1557B is only an estimate as the sediment interval that contained the transition from normal to reversed polarity was not recovered.

A smooth demagnetization curve and an interpretable orthogonal vector plot was observed for the lithified sediment sample from the sediment/basement interface, while the nonlithified sediment returned spurious results. The direction of the lithified discrete sediment sample (inclination ~37°, declination ~128°) calculated from the characteristic remanent magnetization (ChRM) using principal component analysis between 30 and 60 mT is lower than that expected for a GAD at this latitude (30°S). This result cannot be accounted for by magnetic secular variation and is likely due to inclination shallowing as a result of compaction by the overlying sediment column. Analysis of further discrete samples should help elucidate this inclination discrepancy. The median destructive field and coercivity spectra for this sample suggest a magnetite-like phase is the dominant magnetic carrier.

Age Model and Mass Accumulation Rate

The most obvious feature of the age model for Site U1557 is a large hiatus or condensed interval spanning the early Oligocene to middle Eocene. This interval also separates the relatively low

sedimentation rates of the Recent to the Oligocene with the high sedimentation rates of Eocene and Paleocene. Sedimentation rates average 0.77 cm/ky in Unit I (except in the condensed interval, Unit IE, which has a sedimentation rate of 0.17 cm/ky and would bring the overall Unit I average down to 0.57 cm/ky) and 2.24 cm/ky in Unit II. The highest sedimentation rate, 11.53 cm/ky, occurs in the late Paleocene of Unit II. Mass accumulation rates at Site U1557 are primarily driven by carbonate accumulation, with periods of carbonate compensation depth (CCD) shoaling resulting in less carbonate dilution of aeolian dust flux. A surprising result at Site U1557 is the elevated organic carbon content. Total organic carbon values as high as 3 wt% are generally not expected in a midlatitude gyre setting, and the organic carbon accumulation rate (OCAR) suggests that the Paleocene and Eocene were characterized by high organic carbon production and preservation, with a peak near 0.1 g/cm^2/ky. The general correspondence of high OCARs with high carbon accumulation rates indicates overall high productivity in surface waters during this time interval.

Physical Properties and Downhole Measurements

Physical properties characterization of the sediment section at Site U1557 is based on cores and in situ downhole measurements from Holes U1557A and U1557B. Whole-round core-based measurements include natural gamma radiation (sensitive to the abundance of minerals containing radioisotopes of K, U, and Th; [NGR]), bulk density from gamma ray attenuation (GRA), MS (an indicator of the abundance of magnetic minerals), and *P*-wave velocity. Trends in the physical properties recorded downhole within Hole U1557B correlate with lithologic units.

NGR values in Unit I show high-frequency variability between 7 and 50 counts/s, reflecting the alternating carbonate and silty clay layers. In contrast, Unit II is characterized by uniformly lower NGR values, with a mean value of 6 counts/s. Similar trends are present in MS data, which alternates between ~40–50 instrument units (IU) and 100–150 IU within Unit I, and are generally below ~50 IU and less variable within Unit II, reflecting the more uniform, carbonate chalk-dominated lithology. Within Unit II, concomitant abrupt increases in NGR and MS suggest short-lived possible carbonate dissolution events, likely associated with shoaling of the CCD at the time of deposition of these sediments. Bulk density and *P*-wave velocity generally increase with depth in the sedimentary section, which is consistent with carbonate lithologies being denser than the silty clays and an overall compaction trend.

Data from cores recovered using the APC/XCB system in Holes U1557A and U1557B is correlated based on changes in bulk density, MS, NGR, and luminosity (L*) data. The lack of correspondence in the physical properties between Core U1557A-1H and Core U1557B-1H, suggests at least 4.1 m is missing from the top of Core U1557A-1H, which was a missed mudline core. A shipboard splice for the upper 15 m core composite depth below seafloor (CCSF) at Site U1557 is produced with a small splice gap between the bottom of Core U1557B-1H and the top of Core U1557A-1H.

Three downhole temperature measurements were made at Hole U1557B using the advanced piston corer temperature tool and a geothermal gradient of 34°C/km is calculated, similar to the reported upper range at Site U1556. Sixty thermal conductivity measurements yield an average of 1.4 ± 0.25 W/(m·K) with a discernible downhole increase to 1.6 W/(m·K) near the sediment/basement interface. Using temperature and thermal conductivity measurements, a heat flow of 48 mW/m^2 for Hole U1557B is calculated.

Geochemistry

Approximately ~565 m of sediment was cored in Hole U1557B during Expedition 390C, with headspace gas and interstitial water (IW) whole rounds taken once per core. A total of 61 IW samples were squeezed under a laboratory atmosphere. During Expedition 390C, shipboard IW analyses included pH, salinity, alkalinity, major cations and anions (sodium, calcium, magnesium, potassium, chloride, and sulfate) using ion chromatography, major and minor elements using inductively coupled plasma–atomic emission spectroscopy (ICP-AES), and nutrients (phosphate and ammonium). Carbonate and total organic carbon were then analyzed on the squeeze cakes. Depth profiles of redox-sensitive elements in Hole U1557B suggest dissolved oxygen depletion in the upper ~100 m. We observe decreasing sulfate concentrations, a dissolved manganese (Mn) peak, and increasing ammonium associated with organic carbon decay. Increasing sulfate concentrations combined with Mn concentrations near the limit of detection below 280 mbsf may suggest input of oxygenated fluids from the basement. A sharp change in measured alkalinity, as well as calcium, magnesium, boron, and lithium concentrations near the bottom of the hole (~540 mbsf) could also be associated with basement fluid flow. Elevated dissolved silicon (Si) concentrations at ~3 and ~150 mbsf may be indicative of biogenic silica dissolution at those depths.

Basement

Igneous Petrology

Two holes at Site U1557 recovered basement rocks in the form of sedimentary breccia. In Hole U1557B, 9.5 m of sedimentary breccia were cored after basement was reached at 564.8 mbsf. Expedition 390 cored 109.1 m of basement in Hole U1557D, recovering sedimentary breccia throughout the depth of the hole. The breccia consists of a range of basaltic clast types derived predominantly from pillow lavas. The clasts are all moderately to highly altered, obscuring many aspects of primary igneous lithology. Therefore, for the purposes of macroscopic core description, we have distinguished between palagonite and basalts (cryptocrystalline to microcrystalline) and grouped the basalts into three categories based on color that broadly reflect different degrees of alteration: gray, brown, and orange. In general, gray basalts are the least altered and most diverse lithologically; they range from cryptocrystalline to microcrystalline and from aphyric to highly plagioclase-olivine-clinopyroxene phyric, although aphyric is most common. Brown and orange basalts are typically aphyric to sparsely plagioclase or olivine phyric. In addition, orange basalts are associated with textures indicative of an origin in a pillow

chilled margin. With few exceptions, basaltic glass is completely altered to palagonite throughout the core. While some variation in clast lithology is observed downhole, systematic variations were not identified, and the entire sequence of rocks recovered has been defined as a single lithologic unit. It has been subdivided into three lithologic subunits based on variations in breccia matrix and cement.

Metamorphic and Alteration Petrology

Alteration in the breccias at Site U1557 is variable, with evidence of alteration prior to brecciation and redeposition, as well of overprinting alteration in the breccia pile itself. The overall range of alteration is very similar in color, extent, and mineralogy to what was observed at Site U1556, ~6.5 km away, with the major difference at Site U1557 being that clasts of variable alteration have been fragmented and juxtaposed in a breccia where they are further altered in situ. Veins are rare, with only ~300 logged and just under 50 occurrences of vesicles recorded in total. Most of the logged mineral fill consists of breccia cements. The interclast space of the breccias is filled by pelagic sediment, fine grained igneous material (glass and basalt), carbonate, and/or authigenic zeolite "sediment," with open porosity common throughout much of the hole. The volume proportion of porosity and cement decreases downhole.

Paleomagnetism

Progressive AF demagnetization of basement split core sections and discrete samples are used to characterize the paleomagnetic signal and resolve the magnetization components recorded in Site U1557 cores. The NRM of core sections were measured at 2 cm intervals on the SRM. Three AF steps (5, 10, and 20 mT) were applied and the remanence was measured after each step. Discrete sampling was accomplished for Hole U1557D with 13 8 cm^3 discrete cubes collected across the 14 recovered cores from sufficiently big clasts that displayed diverse grades of alteration. Here, we use these data to primarily characterize the magnetic mineral assemblage. Anisotropy of magnetic susceptibility (AMS) was measured on all collected discrete samples in order to characterize the fabric. Acquisition of isothermal remanent magnetization (IRM) and backfield IRM experiments were performed on two representative discrete samples.

Histograms of the inclinations measured on the SRM suggest that the inclinations at Hole U1557D sweep the full spectrum of values from −90° to 90° and cluster around 7°. This is much shallower than the inclination expected for this latitude for a GAD (±49.1° at 30°S). This large departure from that GAD inclination is likely a function of sampling the large clasts from the sedimentary breccia, which should produce randomly oriented directions if the ChRM was blocked before clast emplacement. Every discrete breccia sample displayed stable demagnetization data of a single component that describes a straight line to the origin that defines the ChRM. Inclinations from the calculated ChRM directions verify the inclinations measured from SRM. Additionally, all discrete samples gave maximum angular deviation (MAD) angles <15°. Acquisition of IRM and backfield IRM experiments illustrate the "softness" of the involved ferromagnetic assemblage. The coercivity of remanence (Bcr) values are around

20 mT, the S ratios are equal to 1, and the SRM_{100}/SIRM ratios are 0.99 and 1 respectively in the two studied samples. These values are indicative of the presence of soft ferromagnetic phases as remanence carriers likely dominated by either titanomagnetite or titanomaghemite. AMS indicated the presence of both oblate (planar) and prolate (linear) ellipsoids with no consistent directions or particular distribution along the basement rock package.

The "conglomerate test" was employed to test whether the ChRM in the clasts was blocked prior to their emplacement in the sedimentary breccia or were reset at a later stage. ChRM directions plot randomly about the stereonet, indicating passage of the conglomerate test and that the ChRM of the clasts has been stable after incorporation in the clastic rock. However, the soft nature of the ferromagnetic assemblage suggests that the actual measured components may represent an earlier remagnetization, resulting from alteration (maghemitization) of the original magnetic component on the parent rocks. This result likely means no secondary alteration events took place between clast emplacement and core retrieval.

Physical Properties and Downhole Measurements

Basement physical properties were determined primarily from cores and downhole logging data from Hole U1557D, with additional information from the deepest cores from Holes U1557B, which extended several meters into basement. Measurements on whole-round and split half sections were compared with downhole measurements from Hole U1557D for lithostratigraphic characterization and integration of core description and borehole data. In addition to the standard whole round and discrete measurements, high-resolution 3-D exterior images were also taken from ~70 m of hard rock whole-round cores using the DMT core scanner.

In the basement interval of Site U1557, NGR, MS, and GRA bulk density values from core logger data show no obvious trends with depth in basement. NGR values range from 0 to ~30 counts/s, MS values range from 0 to 800 IU, and GRA values generally cluster around ~2.5 g/cm^3. Bulk density, porosity, and *P*-wave velocity from discrete samples show good agreement with the alteration described for the basalt clasts in the breccia. Additionally, discrete samples show the breccia matrix porosity increases with depth while the *P*-wave velocity of the matrix samples decreases with depth. Electrical resistivity from wireline logging is sensitive to formation porosity and qualitatively agrees with the trends seen in the discrete samples. Thermal conductivity values in basement cores range from 1.1 to 1.8 W/(m·K) and qualitatively appear to decrease with depth in agreement with the discrete sample porosity and wireline resistivity data.

Geochemistry

For the U1557B and U1557D basement cored during Expeditions 390C and 390 respectively, representative samples were taken from the fresh basaltic clasts in the volcaniclastic breccia to obtain a downhole record of the primary magmatic conditions. Lithology of clasts includes gray plagioclase-olivine phyric basalt, yellow-brown phyric basalt, and equigranular basalt. Additional basalt samples with different styles of alteration were chosen to investigate alteration effects on elemental compositions. A total of 20 samples were selected from Hole U1557D and

one sample was taken from Hole U1557B for loss on ignition (LOI) and bulk rock geochemical analysis on ICP-AES. LOI varies between 0.09–~3.85 wt%, with higher LOI in Hole U1557D samples indicating more alteration. Most samples are categorized as alkaline basalt with normal mid-ocean ridge basalt composition based on high field strength element ratios (Zr/TiO_2). Alteration leads to more enriched siderophile elements (e.g., TiO_2, Fe_2O_3, Sc, and V) and large-ion lithophile elements (e.g., Na_2O, K_2O, and Ba) with lower MgO concentrations.

Microbiology

Microbiology sampling in basement at Site U1557 during Expedition 390 was focused on exploring evidence for life in basement using microscopy, culture-based approaches, and culture-independent approaches. No microbiology samples were collected from Hole U1557B, which was drilled during Expedition 390C, when there were no scientists onboard to process the ephemeral microbiology samples. For Hole U1557D, sampling efforts were focused on collecting a single whole-round core sample from each 9.5 m advance that would be processed and subsampled for different analyses. The aim was to generate a suite of samples that were representative of the different rock types and alteration styles that comprise the volcanic basement stratigraphy of the site. In total, 12 whole-round samples (8–15 cm long) were collected for microbiological analysis. The lithology of all samples collected was sedimentary breccia.

Twelve samples were processed for cell counts, shore-based DNA (polymerase chain reaction [PCR] amplicon-based and metagenomes), and/or RNA (PCR amplicon-based and/or metatranscriptomes) analysis; eight samples were preserved for single cell genomics; and seven samples were collected for lipid analysis. Microbial isolation experiments using enrichment media in petri dishes were initiated for Samples U1557D-5R-5, 37.5–48.5 cm, and 7R-3, 0–9.5 cm, on petri dishes with 1/10 ZoBell Marine Agar media. This media selects for heterotrophic marine microorganisms and is commonly used to isolate new microorganisms. Samples U1557D-6R-3, 39–49 cm, and 8R-3, 52–63 cm, were used to initiate stable isotope probing experiments to determine proportions of the microbial community that use specific carbon and nitrogen compounds. Three samples of drill fluid were collected from a pipe on the rig floor during coring operations in Hole U1557D: Core U1557D-2R (586 mbsf), 11R (645 mbsf), and 14R (676 mbsf). Samples were collected for cell counts and shore-based molecular biology analysis to determine the microorganisms present in drill fluid.