IODP Expedition 376: Brothers Arc Flux

Site U1528 Summary

Background and Objectives

Site U1528 (proposed Site UC-1A) is located inside a small (~40 m diameter at the top, ~25 m diameter at the bottom) pit crater at the summit of the Upper Cone of Brothers volcano, in a water depth of 1228 m. The primary objective at this site was to drill into the upflow zone of a hydrothermal system (Type II) strongly influenced by magmatic degassing. In this area, relatively gas-rich, very acidic fluids are being discharged, resulting in advanced argillic alteration. Site U1528 will address important Expedition 376 objectives related to the role of magmatically influenced hydrothermal fluids in transporting metals to the seafloor, and will provide a comparison of fluid-rock reactions with the seawater-dominated hydrothermal system (Type I) drilled at Site U1527.

Operations

We implemented operations in four holes at Site U1528 (proposed Site UC-1A). Hole U1528A is located at 34°52.9177′S, 179°4.1070′E, in a water depth of 1228.4 m. In Hole U1528A, we used a rotary core barrel (RCB) to core from the seafloor to 84.4 m with recovery of 17.1 m (20%). The downhole conditions encountered in Hole U1528A dictated the need for deploying a reentry system to achieve our objectives. Hole U1528B is located 10 m to the south of Hole U1528A at 34°52.9222′S, 179°4.1077′E, in a water depth of 1229.4 m. Here, we drilled in 10¾ inch casing to 24.3 m, with the drilling assembly penetrating to 25.6 m. We had trouble extracting our drilling assembly from the reentry system, which ultimately took us several hours to accomplish. Because of drilling-induced suspension of sediment in the surrounding seawater, visibility was limited and we could only see the top of the reentry funnel. The funnel of the reentry system was observed in a water depth of 1224.8 m, which was consistent with it being properly set on the seafloor. After two separate unsuccessful attempts at reentering Hole U1528B with both the RCB coring system and the turbine-driven coring system (TDCS), we suspended our operational efforts in Hole U1528B. Further visual observations showed a slight angle of the reentry system which prevented the drill string from passing through the throat of the reentry funnel.

Our next objective was to perform the very first offshore test of the TDCS. In Hole U1528C, which is located at 34°52.9215′S, 179°4.1128′E, in a water depth of 1229.1 m, we TDCS drilled without coring to 22 m, then cored to 53.5 m, with a recovery of 3.6 m (12%). Further advancement was prevented by a broken core barrel that remained in the TDCS bottom-hole assembly (BHA). This forced us to abandon operations in Hole U1528C. We then installed casing in Hole U1528D, which is situated at 34°52.9219′S, 179°4.1164′E, in the very limited, flat central area of the pit crater, in a water depth of 1228.1 m. Here, we drilled in 13⅞ inch casing to 59.4 m, with the drilling assembly penetrating to 61.3 m. We then RCB cored to 359.3 m and recovered 87.2 m (29%) under good hole conditions. After the bit had reached 40 h of rotation time, whereupon it would normally be changed before continuing to core, we instead decided to make borehole temperature measurements and obtain fluid sampling in the open hole through the existing bit. The Elevated Borehole Temperature Sensor (ETBS) tool was deployed and it recorded a maximum temperature of 37.6°C at the bottom of the hole. The subsequent deployment of the 1000 ml Kuster Flow-Through Sampler (KFTS) tool ended with its failure under compression in the open hole. After losing the KFTS, we made an unsuccessful attempt to recover the tool with a fishing tool BHA equipped with boot-type junk baskets. Reentry of Hole U1528D was complicated by a plume emanating from the reentry funnel. We then deployed a logging BHA so that we could obtain downhole wireline log data and make another attempt to collect borehole fluids. We deployed our backup 600 ml KFTS tool on the core line and successfully recovered a fluid sample from 279 m. A subsequent ETBS downhole temperature measurement at the same depth recorded a maximum temperature of 212°C. This enabled the flasked wireline high-temperature triple combo (HTTC) logging tool string (natural gamma ray, litho-density, and temperature tools) to be deployed. We successfully performed two upward logging passes from 323 m. Another deployment of the KFTS tool then recovered a second borehole fluid sample from 313 m, followed by another deployment of the ETBS tool which recorded a maximum temperature of 165°C. Next, we drilled down with a tri-cone bit to clean out the hole to 356 m, the depth of the top of the lost KFTS tool.

The next operation was the deployment of a concave mill bit along with two boot-type junk baskets to attempt to remove any remaining parts of the lost KFTS tool. After reentering Hole U1528D for the sixth time—despite very poor visibility around the reentry funnel—we advanced the mill bit to the bottom of the hole at 359.3 m. However, the drill string and junk baskets did not recover any evidence of the KFTS tool. The next fishing attempt involved the reverse circulation junk basket (RCJB), which was assembled in conjunction with the boot-type junk baskets. With the seventh reentry of Hole U1528D we worked the RCJB BHA back to bottom (359.3 m) where we circulated a 25 barrel high-viscosity mud sweep and circulated for ~15 min while working the RCJB up and down. We then pulled the drill string out of the hole. When the end of the drill string cleared the rig floor, we discovered that the lowermost 172.8 m of the drill string was missing, which ended Hole U1528D operations. The drill string failed in a piece of 5 inch pipe above the BHA. The broken piece that was recovered showed significant damage directly attributable to the corrosive downhole environment.

Principal Results

Igneous Petrology and Volcanology

Rocks cored at Site U1528 are subdivided into three lithological units. Igneous Unit 1 was recovered in Hole U1528A (0–6.03 m) and Hole U1528C (26.50–31.41 m) and consists of polymict lapilli tephra made up of subangular to subrounded volcanic clasts that have experienced varying degrees of alteration. Igneous Unit 2 was recovered in Hole U1528A (16.30–83.57 m), Hole U1528C (35.50–46.00 m), and Hole U1528D (61.30–269.30 m), and is divided into three subunits based on internal rock fabric and the presence of primary minerals. Subunits 2a and 2c are composed of sequences of altered lapillistone and lapilli-tuff, with subordinate intervals of altered tuff and tuff-breccia. Clasts are volcanic in origin and altered to differing degrees; the matrix consists of secondary mineral assemblages. Identification of original lithologies becomes increasingly more difficult with depth (especially in Subunit 2c). More coherent dacitic lavas, affected by a lesser degree of alteration, occur from 152.90–160.17 m and make up Subunit 2b. Igneous Unit 3 was recovered exclusively in Hole U1528D (162.50–269.03 m) and consists of altered dacite lava with some relatively unaltered intervals.

The dacitic pyroclastic rocks and lavas at Site U1528 are pervasively altered, yet still show distinct similarities in petrography and bulk rock geochemistry to fresh volcanics encountered in Igneous Unit 1 at Sites U1527 and U1529. Even though intervals with (partially) fresh phenocrysts are rare, primary igneous textures, such as vesicles, and the crystal shapes of plagioclase and (rarely) pyroxene phenocrysts and microlites—now infilled and replaced by secondary minerals—can be recognized in most samples. Petrography and the abundance of elements that are less affected by alteration suggest that the Site U1528 protolith was dacitic tephra and lava similar to those previously encountered at Brothers volcano.

Alteration

Four distinct alteration types are observed in core material recovered from Site U1528. Alteration Type I (0–35.76 m) occurs within unconsolidated gravels and is classified as slightly altered. The dominant alteration mineral assemblage consists of smectite with minor pyrite, cristobalite, natroalunite, pyrophyllite, and native sulfur. Two distinct volcanic clast colors are observed, with dark gray clasts containing more smectite relative to light gray clasts. Native sulfur occurs in two different grain morphologies: crystalline-tabular (orthorhombic) and globular forms.

Alteration Type II occurs in several intervals throughout Site U1528 (e.g., 148.1–150.5 m) and is characterized by an alteration mineral assemblage of illite, smectite, cristobalite, quartz, pyrite, and anhydrite. Alteration Type II is classified as highly altered, and is typically blue-gray in color, brecciated, and exhibits a relict perlitic texture. Plagioclase phenocrysts are variably pseudomorphed by alunite and anhydrite, while pyroxene is pseudomorphed by anhydrite, smectite, and pyrite. The latter is abundant (average of 1–5 vol%) and occurs not only in pyroxene pseudomorphs but also as subhedral to euhedral disseminated grains, and within discrete veins associated with anhydrite. Primary titanomagnetite is rimmed, and then shows progressive replacement by pyrite that exhibits a skeletal texture and contains abundant anhydrite inclusions.

Alteration Type III is intercalated with Alteration Type II (e.g., 239.3–268.1 m), where the boundary between these alteration types can be either gradational or sharp. Alteration Type III is represented by pervasively altered volcaniclastic rocks, white-gray in color, and classified as highly to intensely altered. A mineral assemblage of natroalunite, pyrophyllite and rutile, with lesser quartz, cristobalite, smectite, pyrite, and anhydrite characterizes Alteration Type III. Alunite, pyrophyllite, and silica are more abundant in the matrix, while smectite is enriched in clast material. Plagioclase and pyroxene are completely pseudomorphed by alunite, anhydrite, and pyrite. Late-stage anhydrite-pyrite veins commonly cut pseudomorphed plagioclase crystals. Titanomagnetite is almost completely replaced with leucoxene and pyrite. Vugs are infilled with anhydrite and minor pyrite, native sulfur, alunite, and silica. In addition, fine-grained pyrite occurs finely disseminated throughout matrix and clasts.

Alteration Type IV forms discrete to diffuse white veins that cut and postdate Alteration Types II and III. Alteration Type IV is first observed at 77.2 m and occurs until the cored bottom of Hole U1528D recovered from 355.1 m. It is characterized by an alteration assemblage of natroalunite, anhydrite, rutile, quartz, cristobalite, native sulfur, and pyrophyllite. Mineralogically, Alteration Type IV is distinguished from Alteration Types II and III by higher abundances of native sulfur, silica, and rutile. This alteration type occurs as discrete white veins and distinct alteration haloes typically <1 cm but occasionally up to 4 cm wide, commonly with a vuggy texture, overprinting previous alteration and often preserving earlier alteration textures. Pyrite is generally absent, or oxidized to Fe-oxyhydroxides within the haloes, and native sulfur is the major mineral phase infilling vugs.

Structural Geology

Site U1528 has several structures across Holes U1528A, U1528C, and U1528D, including volcanic fabrics, alteration veins, and fractures. Volcanic fabrics are best observed in Hole U1528A and U1528D and are defined by vesicles and plagioclase microlites (primary and altered) and, to a lesser extent, phenocrysts. Volcanic fabrics have two forms: those within volcanic clasts and in continuous intervals. Volcanic fabrics within clasts can be weak to strong, but each clast has a distinct orientation, suggesting brecciation after fabric formation. Fabrics over continuous intervals typically have a shared orientation and tend to have dips greater than 45°. Peaks in volcanic fabric intensity are observed in Igneous Subunit 2b and Unit 3 in Hole U1528D.

Alteration veins occur throughout Holes U1528A and U1528D and across all igneous units and alteration types. Veins are most commonly filled by anhydrite, pyrite, silica, and native sulfur. Veins are typically uniform, but can be vuggy and some have haloes. The presence of haloes is the basis for Alteration Type IV. Vein density is highest between 100 and 190 m, which is coincident with a peak in native sulfur and vuggy veins and with a deviation in borehole temperature. Vein dip is variable, ranging from horizontal to vertical, with an average of ~60° in both holes. The distribution of dips downhole is variable, with a few zones having a large range in dip (e.g., 0°–90°) and other zones having dips greater than 45°. Vein thickness ranges from 0.05 to 1 cm and averages ~0.2 cm. Vein thickness is variable downhole, but it appears to increase in intervals with a large range of vein dip and thicker veins tend to have steeper dips.

Fractures were observed in all three holes, but their abundance is limited. Fractures in Hole U1528C are irregular and lined with native sulfur. Native sulfur is more abundant where the fractures are the most irregular. In Hole U1528D, fractures are typically clustered in the top 175 m of the hole and have steeper dips (i.e., greater than 60°). Fracture density has three peaks, with the one near 290 m coinciding with a deviation in borehole temperature and a large range in vein dip.

Geochemistry

Geochemical analysis of 75 powders from Hole U1528D was performed via inductively coupled plasma–atomic emission spectroscopy (ICP-AES) for major, minor, and trace elements, and via elemental analysis for total C, total N, and total S. Results of these analyses were used to define major geochemical changes during hydrothermal fluid-seawater-rock interactions in Hole U1528D.

Variable extents of depletion in alkalis (K, Na), Mg, Fe, and Mg, as well as strong enrichment in S (up to 15 wt%), occur throughout the hole. In Igneous Unit 1, Zr/Ti values range from 30.0 to 31.3, and are indistinguishable from average Zr/Ti values for Igneous Unit 1 of Hole U1527A and Site U1529 (i.e., 30.5 ± 2.3). This suggests that the upper lavas and tephra units recovered at Sites U1527, U1528, and U1529 may derive from similar parental magmas. Considering that Y is relatively mobile under hydrothermal conditions in contrast to Zr, the Y/Zr value of altered volcaniclastics is used as a tracer for the extent of alteration. Two main intervals are characterized by lower Y/Zr values (i.e., relative to unaltered dacite from Brothers): (1) 46 to 95.5 m within Igneous Subunit 2a is dominated by Alteration Type III, and (2) 240 to 325 m, overlapping with Igneous Subunit 2c and Unit 3 has alternating Alteration Types II and III.

Based on average compositions of discrete intervals throughout the entire 350 m thick section at this site, we estimate that about >75% of both Mn and Mg have been lost at this site due to hydrothermal alteration. Other significantly depleted elements include Na and K (>50% loss of each element), as well as Ca and P (>30% loss of each element). Total S concentrations vary between 2.1 and 15.1 wt% due to the formation of S-dominated secondary minerals (e.g., alunite, native S, pyrite, anhydrite), although anhydrite represents a minor component of the total S inventory, based on water-soluble elemental analysis by ICP-AES. Iron appears to be strongly depleted in late-stage Alteration Type IV, suggesting that pH, fO_2, and fS_2 conditions changed substantially from Alteration Types II/III, leading to extensive loss of Fe in possibly SO_4-rich, but H_2S-poor, hydrothermal fluids. Similar to Site U1527, organic carbon comprises the bulk of measured total carbon concentrations but remains very low, yielding an average of about 250 µg/g at Site U1528.

One sample of interstitial water has a low pH value of 4.1, consistent with the presence of acidic magmatic fluids. Near equimolar enrichments in Ca and SO_4 suggest that the dissolution of anhydrite at low temperatures may be occurring in the pore waters.

Two borehole fluid samples were collected from Hole U1528D using the KFTS tool at approximate depths of 279 m and 313 m. Maximum estimated temperatures of 212°C and 247°C, respectively, were determined by downhole logging. The fluids have nearly identical Cl, Br, Mg, and Sr contents, and similar Na concentrations that are all lower than seawater. Highly elevated ΣSO_4 and very acidic pH values (as low as 2.1) are characteristic of acid sulfate fluids. The fluids are also highly gas-rich. This fluid may either represent unaltered seawater mixing with direct input from a low-salinity magmatic volatile-derived fluid, mixing with the vapor phase of a phase-separated, seawater-derived parent fluid ($Cl_{fluid} < Cl_{seawater}$), and/or a combination of fluids derived from all three origins. Elevated Si and K contents in the fluids are due to the likely dissolution of Si- and K-bearing minerals in the presence of highly acidic fluids.

Gas headspace components, including H_2, CO_2, and acid volatile S, are elevated over ambient atmospheric levels. These gas anomalies may derive from subseafloor hydrothermal fluid input of volatile-rich fluids that share similar chemical properties with the seafloor hydrothermal fluids discharging at the Upper and Lower Cone sites.

Paleomagnetism

At Site U1528, the natural remanent magnetization (NRM) of 83 archive-half sections were measured and alternating field (AF) demagnetization experiments were conducted using the cryogenic superconducting rock magnetometer (SRM). The sections show generally low NRM intensities where the largest pieces have primary magnetization components, after AF steps of 20 mT, with negative inclinations suggesting normal polarities. AF and thermal demagnetization experiments on 82 discrete samples from Igneous Units 2 and 3 were also carried out. The drilling-induced overprint is generally removed after 20 mT AF demagnetization on the discrete samples leaving, in most cases, a stable primary magnetization. The two igneous units have very low NRM intensities, in agreement with the observations from the SRM. However, both units show a consistent direction of magnetization with average inclination compatible with the inclination of a geomagnetic axial dipole of −55°, which is the present-day latitude of Brothers volcano. This suggests a coherent young age for these rocks, most certainly during the current normal polarity Brunhes Geomagnetic Epoch. Thermal demagnetization experiments from these units show a complex pattern suggesting irreversible transformation of magnetic minerals during heating to >400°C; this is confirmed by changes in the magnetic susceptibilities measured with the Kappabridge susceptibility meter before and after heating. In addition, isothermal remanence magnetization experiments suggest that these rocks contain minerals with large magnetic coercivities, such as titanohematite, in addition to titanomagnetite.

Physical Properties

Physical properties measurements for Igneous Unit 1 (Alteration Type I) are consistent with the ranges expected for fresh unconsolidated dacitic volcaniclastics. Within Igneous Units 2 and 3, more complex variations in physical properties associated with igneous unit and/or alteration type are observed. For example, magnetic susceptibility (MS) values are generally higher in intervals of Alteration Type II than Type III, which may be explained by the observed partial replacement of titanomagnetite by rutile and pyrite in the relatively more altered Type III rocks. Downhole measurements also indicate an association between Alteration Type II and increases in natural gamma ray (NGR) attributed to ^{40}K, however this could not be confirmed by NGR measurements in the laboratory due to the fragmented core material that was recovered. The relatively high ^{40}K NGR signal identified in a core from Alteration Type II (Core U1528D-48R-1) is consistent with this observation.

The boundary between Igneous Units 2 and 3 is clearly defined by changes in grain density, bulk density, porosity, *P*-wave velocity, and thermal conductivity, as well as by an increase in MS associated with the concurrent transition from Alteration Type III to Type II. This likely reflects the change in primary igneous lithology from volcaniclastics to massive lavas. By contrast, boundaries between Igneous Subunits within Igneous Unit 2 are clearly defined by variations in physical properties. An interval of relatively lower bulk density and *P*-wave velocity and higher porosity is observed between ~145 and ~220 m, but it is not associated with defined igneous subunit or alteration type boundaries. Instead, this interval corresponds to the depth at which H_2S gas was observed during core splitting, and its boundaries correspond to a borehole temperature anomaly and increased fracture densities, vein thicknesses, and range of vein dip. Hence, in this depth interval, physical properties may identify a zone related to the current hydrothermal system that cuts across identified igneous units and alteration types.

Downhole Measurements

A series of downhole measurements were conducted and borehole fluid samples taken at the end of Hole U1528D coring operations. Three runs of the ETBS tool were completed in Hole U1258D. The first deployment, made prior to logging to help determine what logging tools could be deployed, measused an average temperature at the bottom of the hole of 33°C. After we collected borehole fluid samples using the KFTS at 279 and 313 m, two other temperature measurements were made at these same depths, recording temperatures of 212°C and 165°C, respectively.

A high-temperature, flasked, wireline logging string consisting of lithodensity, NGR, and logging head temperature tools was run to 332 m in Hole U1528D. Variations in the total NGR variations are mostly related to peaks in potassium, generally correlated to Alteration Type II, which is rich in illite. Overall, the downhole density log correlates well with the bulk density measured on the core samples and shows different trends that are generally correlated with the igneous units; (i) from 65 to 145 m (Igneous Subunit 2a), density gradually decreases downhole, (ii) from 145 to 250 m, there is a sharp decrease in density (between 140 and 155 m; Igneous Subunit 2b) followed by a gradual increase with depth (Igneous Subunit 2c), and (iii) from 250 to 330 m, the density is very variable (Igneous Unit 3).

The three temperature profiles acquired during wireling logging suggest a convective temperature regime with small temperature increases at ~100 m and 150 m, and larger increases at ~275 m and 295 m. A temperature reversal (i.e., a decrease in temperature with depth) is observed at ~250–260 m. Over the 2.5 h of logging, the temperature increased by about 8°C in the isothermal zones, and by 24.5°C between 270 and 310 m, reaching 247°C. This suggests that the downhole temperatures had not yet reached equilibrium. The temperature anomalies at ~150 and ~295 m are accompanied by increases in borehole diameter, peaks in potassium, the first instance of sulfur smell emanating from the cores, native sulfur observed in veins, high fracture density with varied fracture dips, crosscutting fractures, and increased vein density. These zones are interpreted as structurally-controlled permeable intervals.

Microbiology

A total of three, one, and 13 whole-round samples (3–16 cm long) were collected for microbiological analysis from Holes U1528A, U1528C, and U1528D, respectively. Lithologies sampled represented the various igneous units recovered. Samples were processed for shore-based DNA and RNA analyses, cell and viral counting, as well as viral and microbial activity measurements. All samples were analyzed onboard for adenosine triphosphate (ATP) concentration, with two samples giving positive values. The other samples contained compounds that inhibited the enzyme luciferase used for the ATP test. Nutrient addition bioassays with inorganic nitrogen and phosphorus, or organic carbon, were initiated to determine the nutritional constraints on biomass in this environment. Perfluoromethyl decaline (PFMD) was used for contamination testing. PFMD was usually detected on the outside of uncleaned cores, and on rare occasions was above detection levels on the cleaned outside of cores. However, it was usually below detection on the inside of cores, indicating penetration of drilling fluid to the interior of whole-round cores (where we collected samples) is unlikely.