IODP Expedition 376: Brothers Arc Flux

Site U1530 Summary

Background and Objectives

Site U1530 (proposed alternate Site NWC-3A) is located on a narrow bench on the northwest Caldera site of Brothers volcano, in a water depth of 1595 m. The primary objective at this site was to drill through the lower part of the Type I hydrothermal system. Site U1530 is located ~400 m east of Site U1527 on a ~30 m long by ~10 m wide bench towards the upper part of the northwest Caldera wall. It is situated structurally above a known prominent metal-rich stockwork zone. The operations plan at Site U1530 was to penetrate ~450 m through the upper stockwork and then deeper portions of the inferred hydrothermal upflow zone, and continue through a thicker stratigraphic section of lavas within the caldera, hoping to intersect the footwall of the original caldera. Intersection of the stockwork was expected to provide the best opportunity to investigate the transport of metals through the Brothers hydrothermal system.

Operations

Operations were conducted in one hole at Site U1530 (proposed alternate Site NWC-3A). Hole U1530A is located at 34°51.6588′S, 179°3.4572′E in a water depth of 1594.9 m. We used a rotary core barrel (RCB) to core from the seafloor to 453.1 m with recovery of 76.8 m (17%). We encountered optimum downhole conditions throughout coring. After successfully penetrating to our target depth, we decided to terminate coring in Hole U1530A to take advantage of the good hole conditions for downhole measurements and fluid sampling. Hence, we released the bit in the bottom of the hole by deploying the rotary shifting tool.

Our downhole measurement plan for Hole U1530A consisted of running (1) the Elevated Temperature Borehole Sensor (ETBS) tool, (2) the Kuster Flow-Through Sampler (KFTS) tool, (3) the triple combination logging tool string ("triple combo," consisting of natural gamma ray, porosity, and density sondes, including magnetic susceptibility, resistivity, caliper, and logging head temperature), (4) the Formation MicroScanner (FMS)-sonic logging tool string, and (5) the Petrospec spool-in Thermocouple Memory Tool (TCMT). After recording a temperature of 40°C at the bottom of the hole (stationary measurement time of 15 min) with the ETBS, we lowered the KFTS on the core line to a depth of ~433 m but could not recover a fluid sample as the valves failed to close completely. We then raised the end of drill string to a logging depth of 67.1 m, lowered the triple combo tool string into the hole, and performed a calibration pass and a full logging run from the fill at 442 m up to the seafloor. This was followed by two logging passes with the FMS-sonic tool string from 442 m to just below the end of the pipe at 51.8 m. We then lowered the end of the drill string to 416.2 m and obtained a borehole fluid sample with the KFTS. Finally, the third-party TCMT was deployed and, with the temperature-sensitive TCMT data logger kept inside the drill string, the two thermocouple joints were lowered 8 m past the end of the drill pipe and held at 447 m for 10 min. This first test of the newly designed high-temperature TCMT recorded a temperature of 20°C. This completed our operations at Site U1530. A total of 184.0 h or 7.7 d were spent on Site U1530.

Principal Results

Igneous Petrology and Volcanology

Five igneous units were identified at Site U1530. Igneous Unit 1 (0–26.62 m) consists of a clast-supported polymict lapillistone with occasional blocks and bombs. Clasts are volcanic in origin and reside in a matrix of altered, smaller volcanic fragments and secondary minerals. Igneous Unit 2 (30.70–59.62 m) consists of a sequence of completely altered tuffaceous mudstone, siltstone, and sandstone with one subordinate horizon of polymict lapillistone, and is subdivided into five Subunits 2a through 2e, based on color, grain size, and internal structures. Igneous Unit 2 displays various sedimentary textures, including normal and reverse grading as well as horizontal, wavy, lenticular, and inclined bedding, indicating transport, depositional, and soft sediment deformation events. Igneous Unit 3 (59.62–64.40 m) consists of altered plagioclase phyric lava with pseudomorphs after glomerocrystic plagioclase. Igneous Unit 4 (64.40–218.21 m) is a sequence of highly altered volcaniclastic rocks, with discernible monomict and polymict lapillistone and monomict lapilli-tuff in the upper half, consisting of altered volcanic clasts in a fine-grained, completely altered matrix. Alteration hinders detailed classification in the lower half of Unit 4. Igneous Unit 5 (222.70–448.68 m) consists of highly altered volcanic rocks with five discrete horizons of less altered, plagioclase phyric lava containing pseudomorphs after glomerocrystic plagioclase.

Despite the pervasive alteration, the volcanic and volcaniclastic rocks retain residual volcanic textures and original compositions of alteration-resistant elements and ratios (Ti, Zr, Ti/Zr), which suggest that the protolith was a typical Brothers dacite. Similar to Hole U1527C volcanic and volcaniclastic rocks, Hole U1530A rocks appear to have the same slight, but systematically lower Ti/Zr value (about 27) compared to volcanic rocks of Sites U1528 and U1529 where the Ti/Zr value is ~36. While this disparity is small compared to the overall range observed in Kermadec arc lavas (i.e., Ti/Zr up to 220), it points towards slight genetic variability among the Brothers dacitic magma series.

Alteration

Five distinct alteration types were identified based on their alteration mineral assemblage in core material recovered from Hole U1530A. All alteration types occur at various intervals downhole, overprinting each other, and therefore cannot be assigned to a certain depth interval.

Alteration Type I is classified as highly to intensely altered and has an alteration mineral assemblage of cristobalite, smectite, pyrite, anhydrite, sphalerite, and barite, with minor quartz, chlorite, and illite. A network of anhydrite-barite veins with fine- to medium-grained sphalerite cuts blue-gray lapillistone. The clasts are variably altered/silicified, and the contacts between clasts and matrix are distinct. Anhydrite is most abundant in veins and only rarely infills vugs within clasts. In one sample, an acicular mineral, most likely natroalunite, is observed microscopically cutting anhydrite-pyrite-silica veins, but is not detected by X-ray diffraction (XRD) analysis.

Alteration Type II, classified as intensely altered, has a characteristic green-gray color and an alteration mineral assemblage of quartz, illite, and chlorite, with variable amounts of anhydrite, pyrite, and smectite. Alteration Type II occurs within three distinct lithologies throughout the hole; tuffaceous fine-grained sediments, coherent lava, and pyroclastic rocks. The abundance of individual alteration minerals varies with lithology. For example, pyrite is more abundant within the fine-grained sediments compared to the pyroclastic rocks. The fine-grained sediment unit is frequently cut by coarse-grained, vuggy, anhydrite veins. The altered lava unit exhibits a vuggy texture, with vugs filled with quartz, anhydrite, and minor pyrite. Chlorite and illite are intergrown with microcrystalline quartz forming a homogeneous matrix. The volcaniclastic unit is characterized by subangular clasts that are visually distinguishable from matrix material. Clasts are rich in chlorite and illite relative to the silica- and pyrite-rich matrix. Plagioclase is completely pseudomorphed by chlorite, quartz, and occasionally smectite.

Alteration Type III, classified as intensely altered, is characterized by an alteration mineral assemblage of quartz and illite, with minor smectite, anhydrite, and chlorite. It is subdivided into two subunits (IIIa and IIIb), based on relative abundances of anhydrite (enriched in Type IIIa) and chlorite (enriched in Type IIIb). Alteration Type IIIa is white-gray and consists of a well-defined pyroclastic texture with soft, illite-rich clasts within a silica- and pyrite-rich matrix. Alteration Type IIIb is blue-gray and both matrix and clasts are intensely silicified. Pyrite occurs as a minor phase disseminated throughout. Iron-oxyhydroxide is likely to be derived from pyrite oxidization. Magnetite is an accessory phase and is frequently resorbed and overprinted by pyrite.

Alteration Type IV is light gray, intensely altered, and has a mineral assemblage of pyrophyllite, quartz, illite, smectite with minor pyrite and rutile. Clasts are poorly defined and strongly resorbed. Pyrophyllite is patchy and intergrown with illite and disseminated fine-grained anhydrite, and likely represents the core of relict clasts. Quartz is intergrown with illite and forms discrete veins associated with subhedral pyrite. Rutile and leucoxene are common, forming <0.1 mm grains, and are variably overprinted by pyrite.

Alteration Type V exhibits a buff color and occurs as two distinct subtextures: fine-grained homogeneous material and coarse-grained, equigranular material with a mottled texture. Both exhibit the same alteration mineral assemblage of diaspore, quartz, pyrophyllite, smectite, rutile with minor illite, pyrite, and anhydrite. Iron-oxyhydroxide staining is well developed throughout this alteration type, and pyrite is absent in some samples. Vugs are abundant and commonly infilled with chalcedony with anhydrite filling the core of the vug. Anhydrite occurs in two distinct generations; coarse euhedral grains that infill vugs and veins, and a fine-grained subhedral to euhedral form intergrown within the matrix. Rutile occurs in traces, being mantled or overprinted by pyrite.

Structural Geology

Structures in Hole U1530A consist of volcanic fabrics, alteration veins, fractures, and sedimentary boundaries. Sedimentary boundaries, defined by changes in grain size and/or texture, are all sub-horizontal (<10°). Volcanic fabrics are in two forms; within volcanic clasts or within coherent lava. In both forms, the fabric is defined by vesicles and plagioclase microlites. Volcanic fabrics within volcanic clasts can be weak to strong, but do not share a common orientation across clasts. This type of fabric is observed within the top half of Hole U1530A in lapilli tuffs defining Igneous Units 1 and 4. Moderate-to-strong volcanic fabrics that occur over decimeters define Igneous Units 3 and 5 consisting of lavas. Volcanic fabrics within the lavas tend to be moderate to steep, with dips >45°.

Alteration veins occur throughout the hole and are typically filled with anhydrite, silica, and/or pyrite. Vein density is variable downhole with the highest density related to the presence of network veins, typically filled with pyrite or silica. The largest abundance in network veins is at the very top of the hole from 0–25 m. Discrete veins are most abundant at ~70 m and ~270 m. These depths also correspond to a large range in vein dip (0–90°), an increase in vein thickness and, at ~270 m, a deviation in borehole temperature. These depth intervals are also related to changes in igneous rock type between sedimentary and lavas above lapilli tuffs at ~70 m and a change from lapilli tuff to lava at ~270 m. The presence of sedimentary and volcanic rocks, large range in vein dip and thickness, and a deviation in borehole temperature may indicate the presence of lateral flow zones related to permeability contrasts. Fractures are less abundant compared to veins, but are more common than at any other site. Fractures have a large range in dip and are more abundant at ~55 m and ~255 m, coincident with zones of more abundant veins. Slickenlines were identified from ~190 to 290 m and typically have a steep rake and a normal sense of shear.

Geochemistry

All hard rock samples from Site U1530 were affected by various degrees of hydrothermal alteration, as confirmed by petrographic descriptions and analysis via XRD and inductively coupled plasma–atomic emission spectroscopy/portable X-ray fluorescence spectrometry (ICP-AES/pXRF). Altered volcaniclastic materials and lavas show strong geochemical changes for a large range of elements, with major loss of Mn, Ca, and Na. The observed downhole variations of major oxide and trace elements are much more pronounced at Site U1530 compared with Site U1527, including the extensive loss of Na_2O relative to unaltered dacites recovered at Sites

U1527 and U1529. Other alkali elements, such as potassium (K_2O) as well as the alkaline-earth metals (Mg, Ca, Sr, Ba), show both depletions and enrichments relative to fresh dacites. The strongest geochemical shifts in Hole U1530A occur between 189 and 191 m, with a decrease in K_2O, Ba, Y, and Cu concentrations that correspond to the transition to Alteration Type IV, and the disappearance of illite and first appearance of pyrophyllite. Alteration Types IV and V in Igneous Unit 5 form two important end-members and display the strongest depletions in Mg, Ba, Sr, Fe, Cu, and Zn. The reverse pattern is seen in Alteration Type I in Igneous Unit 1, suggesting that some of the loss of elements observed at the bottom of the hole may be, in part, balanced by a gain of these elements in the upper part of the hole. Depletions in CaO are associated with higher Sr concentrations and the identification of anhydrite by XRD, suggesting that the abundance of CaO is mainly controlled by the occurrence of anhydrite. Principally hosted in barite, Ba at Site U1530 ranges from trace levels of about 20 μg/g in Alteration Types IV and V, to very high abundances of up to about 3 wt% in Alteration Type I. A pronounced correlation is observed between total S and Fe concentrations throughout Hole U1530A, suggesting that pyrite represents the primary form of sulfur in the rock (predominantly in Igneous Units 1, 2, and 4). Significant enrichments in Zn (up to 5.2 wt%), Cu (up to 1760 ppm), As (up to 660 ppm), Pb (up to 100 ppm), and Mo (up to 560 ppm) were also recorded in pyrite-rich intervals consistent with high-temperature hydrothermal fluid contributions.

Total C (TC) abundances in the majority of Hole U1530A samples are less than 200 μg/g, and are overall lower than TC abundances at Sites U1527, U1528, and U1529. An average total S (TS) concentration at Site U1530 of 5.1 wt% is similar to the 5.9 wt% average at Site U1528. In contrast to Site U1528, however, TS concentrations decrease with depth from about 11 wt% to about 3.5 wt% on average.

Headspace dissolved gases, including H_2, CO, CH_4, C_2H_6, CO_2, and H_2S were analyzed from several intervals of the recovered cores in Hole U1530A. As reported at Sites U1527, U1528, and U1529, headspace dissolved C_2H_6 concentrations were below detection limit (<0.03 μM) for all the depths of Hole U1530A. Five intervals with elevated H_2, CH_4, CO_2, and Acid Volitile Sulfide (AVS) concentrations were detected. Maximum pore-fluid AVS and $\sum CO_2$ concentrations of 1.6 mM and 37 mM are similar in concentration to those determined by previous studies for actively venting chimneys of the northwest Caldera vent field, and may originate from fluids rich in magmatic volatiles.

A fluid sample was collected with the KFTS tool at 435 m (at the same depth as Core U1530A-90R). The in situ fluid temperature was estimated to be <38°C based on downhole temperature logging. The borehole fluid sample is slightly acidic relative to seawater, with a pH value of 6.8, and is characterized by the same major and minor species composition (i.e., dissolved Na, K, Ca, Sr, Mg, Cl, Br, SO_4) as drilling fluid (surface seawater) within analytical error. Dissolved ΣH_2S is below detection. The abundances of several metal species are highly elevated above seawater abundances, and are likely derived from contamination by the steel bit and drill string or the KFTS itself.

Paleomagnetism

Natural remanent magnetization (NRM) of 81 archive-half sections from Hole U1530A were measured using the cryogenic superconducting rock magnetometer. The overprint magnetization from drilling and coring was reduced by using the inline alternating field (AF) demagnetizer. Detailed measurements of anisotropy of magnetic susceptibility (AMS), AF and thermal demagnetization, and isothermal remanent magnetization (IRM) experiments on 65 discrete oriented samples were also conducted (four from Igneous Unit 1, five from Igneous Unit 2, two from Igneous Unit 3, 24 from Igneous Unit 4, and 30 from Igneous Unit 5). Magnetic directions for discrete samples show relatively shallow inclinations compared with Sites U1527 and U1528. In particular, three samples from Igneous Unit 2 (Cores U1530A-10R to 11R, 50–55 m) show consistent positive inclinations, which are confirmed by corresponding pieces measured in the cryogenic magnetometer. The NRM intensities and magnetic susceptibilities also highlight relative differences between the various igneous units. For example, Igneous Unit 1 is characterized by low NRM intensities, low coercivities, and erratic thermal demagnetization curves. Igneous Units 2 and 4 are characterized by very low NRM intensities with complex AF and thermal demagnetization curves, but larger coercivities. Igneous Units 3 and 5 show low NRM intensities, low-to-medium magnetic coercivities, and relatively simple AF and thermal demagnetization curves, with a minor overprint from drilling. Igneous Units 1, 2, and 4 also show increases of the NRM intensity after heating to temperatures >400°C, suggesting irreversible transformation of the original magnetic minerals during heating.

Physical Properties

Variations of physical properties at Site U1530 show good correlations with defined igneous units and subunits, but are less well correlated with transitions in alteration types. Igneous Unit 1, which corresponds to Alteration Type I, contains the peak values for magnetic susceptibility (MS) and natural gamma radiation (NGR) at the site. NGR peaks are also recorded by downhole measurements with the Hostile Environment Natural Gamma Ray Sonde (HNGS) and are an order of magnitude higher than those recorded at previous drill sites, being attributed to radioactive U isotopes in the sulfide and barite veins observed at this depth.

Transitions between and within igneous units and subunits are clearly defined by variations in bulk density, porosity, and *P*-wave velocity. These data do not show strong correlation with structural features, such as fractures or alteration veins. Observed variations in MS and thermal conductivity do not correspond clearly to the observed abundance or distribution of particular minerals, but there is a large increase in MS from Igneous Unit 4 to 5.

Overall, physical properties datasets define two intervals of markedly different characteristics between ~30 to ~35 m in Igneous Unit 2 and ~75 to ~85 m in Igneous Unit 4. These intervals are characterized by high grain density, low bulk density, and high porosity. They also correspond to increased concentrations of Fe_2O_3, S, trace metals, and metalloids, and are located directly beneath intervals characterized by increased fracture density and wide ranges in dip angles of alteration veins. These intervals may therefore be important for understanding the past fluid-rock interactions and flow pathways of the hydrothermal system at Site U1530.

Downhole Measurements

Downhole measurements were acquired after coring in Hole U1530A. Multiple borehole temperature measurements obtained over the downhole logging period indicate that the hole warmed from ~35°C to 94°C at around 430 m during the first 5 h after stopping circulation, and then cooled down to 37°C during the subsequent 10 h. The temperature profile showed a gradual increase in temperature with depth, indicative of a largely conductive-dominated regime in the borehole, and also displayed a "concave up" shape suggestive of recharge into the formation. Thermal anomalies in the temperature profiles observed between 255 and 295 m may indicate a permeable flow zone. This interval is also characterized by the highest number of veins with a large range in vein dip and a higher abundance of fractures, suggesting a structural control for this permeable zone. Downhole NGR measurements revealed a high uranium content between 23 and 35 m correlating well with high values measured on the recovered core and most likely being related to barite that has been identified by XRD analysis. High potassium values correspond to Alteration Types II and III, both of which contain abundant illite. Downhole density and porosity measurements agree well with discrete core measurements. The interval between 70 and 85 m within Igneous Unit 4 and Alteration Type IIIa shows low bulk density and high porosity from both discrete and downhole measurements, and also low resistivity. This depth interval corresponds to high grain density and low *P*-wave velocities measured on the cores. Combined, these observations suggest that this interval may be important for understanding past fluid circulation and fluid-rock interactions at this site. Initial observations on the FMS-sonic images indicate the presence of numerous fractures and veins throughout the logged interval.

Microbiology

A total of 18 whole-round samples (5–11 cm long) were collected from Hole U1530A for microbiological analysis. Samples were processed for shore-based DNA and RNA analyses, cell and viral counting, as well as viral and microbial activity measurements. Perfluoromethyl decaline (PFMD) was used for contamination testing, and was usually detected on the outside of uncleaned cores and, on rare occasions, was above detection levels on the cleaned outside of cores. However, concentrations of PFMD in drilling fluid samples were much lower than the expected 500 ppb values. Based on the results, the decision was made to increase the PFMD tracer pumping rate 10× at the next drill site and collect drilling fluid from every core.