IODP Expedition 398: Hellenic Arc Volcanic Field

Site U1591 Summary

Background and Scientific Objectives

Prior to arrival onsite, it was decided to replace the original primary Site CSK-13A by alternate Site CSK-20A, the latter hence becoming Site U1591. This was done to pass through a slightly more complete suite of seismic reflectors.

Site U1591 is located ~8 km northwest of Christiana Island and ~20 km southwest of Santorini in a water depth of ~515 meters below sea level (mbsl). The drill site targeted the Pliocene–Quaternary volcano-sedimentary fill of the Christiana Basin. This basin formed by subsidence along an ENE–WSW fault system in the Pliocene to early Pleistocene, before the changing tectonic regime activated the current NE–SW rift system in which the Christiana-Santorini-Kolumbo (CSK) volcanic field lies.

The Christiana Basin is deeper than the Anhydros and Anafi Basins; its volcano-sedimentary fill potentially records the earlier volcanic history of the CSK volcanic field (including the products of Christiana and early Santorini), as well as younger Santorini and possibly Milos Volcano to the west along the Aegean Volcanic Arc. The now-extinct Christiana Volcano produced lavas and tuffs of unknown ages, but an ignimbrite found on Christiana, Santorini, and the nonvolcanic island of Anafi, called the Lower Christiana Tuff, has the geochemical fingerprint of Christiana magmas and has been dated using the fission track method on zircon at ~1 Ma.

Six seismic units have been identified in the Christiana Basin by previous work. Site U1591 was chosen to pass through Seismic Units U1 to U6, including volcaniclastics from both Santorini and Christiana, and to target the top few meters of the prevolcanic basement below Unit 1. We received permission from the IODP Environmental Protection and Safety Panel (EPSP) to drill to the Alpine basement at this site involving three holes. A gravity core recovered 7 km to the south-southwest indicated that the topmost sediments onsite would be characterized by hemipelagic muds, volcaniclastics, and turbidites, complemented by pumiceous tuffs, debris flows, and continental basement rocks (Mesozoic limestones, schists and/or granites) in the deeper portions.

The aims of drilling at Site U1591 were to accomplish the following objectives:

- Better date the volcanic activity of Christiana using biostratigraphic and magnetostratigraphic means, and find out whether the CSK Volcanic Field had Pliocene volcanism like Milos Volcano further west.
- Relate the Christiana volcanism to subsidence along the ENE–WSW fault sets and to the activation of the NE–SW fault sets and seek the submarine equivalent of the Lower Christiana Tuff.

- Use deeper coring (and seismic profiles) to reconstruct the volcanic, sedimentary, and tectonic histories of Christiana Volcano, and possibly Milos to complement the Santorini and Kolumbo volcanic records of Sites U1589 and U1590, and therefore access a near-continuous time series of volcanism of the CSK Volcanic Field since rift inception.

Site U1591 addresses scientific objectives 1–4 and 6 of the Expedition 398 *Scientific Prospectus*.

Operations

All thrusters were down and secured on 2 January 2023 at 0006 h. The vessel was switched to dynamic positioning (DP) mode and on autocontrol at 0014 h, marking the start of Site U1591 (proposed Site CSK-20A). The transit from Site U1590 took only 2.3 h, covering 20.3 nmi at 8.8 kt.

The operations involved three holes, but with heavier use of the extended core barrel (XCB) and rotary core barrel (RCB) due to the seemingly poor hole conditions when piston coring. Hole U1591A was piston cored with the advanced piston corer (APC) until the hole became unstable at Core U1591A-10H and was ended after Core 11H. Hole U1591B was piston cored to just above the trouble area, drilled down, and then primarily cored with XCB. Core U1591B-43X saw the XCB shoe sheared off, ending the hole. Hole U1591C was an RCB-only hole, drilled to 149.3 meters below seafloor (mbsf) without recovery and then cored to 902.9 mbsf. The hole was terminated for reasons of insufficient time.

At 0740 h on 2 January, Hole U1591A was spudded at 36°18.7615′N, 25°9.0057′E, with a recovery of 3.8 m in Core U1591A-1H, and a calculated seafloor at 514.6 mbsl. Coring with the APC continued to Core 11H at 98.8 mbsf. The string was pulled out of the hole and the bit cleared the rotary table at 1700 h, ending Hole U1591A.

A reconfigured APC/XCB bottom-hole assembly (BHA) was assembled with the same drill bit. The tapered drill collar (TDC) and nonmagnetic (stainless steel) drill collar (NMDC) were removed and stored in the forward collar catwalk. Hole U1591B was spudded at 2150 h on 2 January at 36°18.7621′N, 25°9.0190′E. The recovery of 3.8 m indicated the seafloor was at 513.8 mbsl.

At 0245 h on the morning of 3 January, the APC was pulled and an XCB center bit was dropped. The intention was to drill through a previously identified pumice section. The driller established the slow circulation rates and proceeded to drill without core recovery from 74.1 to 98.8 mbsf. On 5 January, XCB coring finished with Core U1591B-43X at 389.2 mbsf, the final depth for Hole U1591B, after the XCB cutting shoe sheared off in hole. The bit cleared the rig floor at 0950 h, ending Hole U1591B.

On 5 January at 1500 h, Hole U1591C was spudded at 36°18.7810′N, 25°8.9962′E, with an offset water depth of 524.9 meters below rig floor (mbrf). A drill-ahead section was completed to 149.3 mbsf. Coring began with the RCB, from Core U1591C-2R to 13R at 265.0 mbsf. A second drilled interval followed from 265.0 to 350.0 mbsf. RCB recovery was reinstated with Core 15R and continued to Core 71R at 902.9 mbsf, the final depth for Hole U1591C. The decision was made to terminate coring in favor of other objectives. The bit cleared the rotary table at 1550 h on 10 January and the rig floor secured for the transit. Deck hands started raising the thrusters at 1636 h. All thrusters were up and secured at 1648 h, and the sea passage to Site U1590 (proposed Site CSK-03A) began, ending Site U1591.

Principal Results

Cores from three consecutive holes at Site U1591 recovered a partial stratigraphy from 0 to 902.67 mbsf. Hole U1591A consists of Cores 398-U1591A-1H through 11H (0–90.85 mbsf), Hole U1591B contains Cores 398-U1591B-1H through 43X (0–386.57 mbsf), and Hole U1591C includes Cores 398-U1591C-2R to 71R (149.3–902.67 mbsf). We observed a very good correlation between Holes U1591A and U1591B. Recovery at Hole U1591C begins with Core 3R at 158.3 mbsf to Core 13R at 265.0 mbsf, with the goal of recovering volcanic intervals encountered between Cores 398-U1591B-18F-CC and 22X-1 from Hole U1591B, where recovery was low. Following a second drilled interval, it was decided also to duplicate the rest of Hole U1591B below 350 mbsf, as much of the record recovered with XCB drilling was heavily biscuited. In addition, Hole U1591C targets the lithology of the underlying basement.

The recovered material is sedimentary and unlithified in all of Hole U1591A and Hole U1591B. There is a gradual transition to stiffer and more consolidated material towards the bottom of Hole U1591B, and this continues in Hole U1591C. Sediment in Hole U1591C in turn transitions gradually from consolidated sediment to sedimentary rock. The sedimentary succession in the upper 772 m is characterized by both volcanic lithologies (ash/tuff, lapilli-ash, lapilli, and tuffaceous mud/sand/mudstone/sandstone) and nonvolcanic calcareous mud/mudstone and ooze/marl. At 772 mbsf there is a sharp transition from marls, calcareous mudstones, and micrites to nodular anhydrite-bearing lithologies (± algal mats).

Changes in relative abundances of volcanic lithologies and oozes/marls enables definition of the first two lithostratigraphic units at Site U1591, Unit I and Unit II. Unit I is dominated by extensive volcanic intervals with lesser overall amounts of nonvolcanic material, whereas Unit II is dominated by oozes/marls and calcareous muds/mudstones with lesser volcanic intervals. The third lithostratigraphic unit (Unit III) is marked by the onset of lithologies containing evaporitic sequences.

Structural geology analyses included description of cores retrieved from Holes U1591A to U1591C. A total of 535 structures were measured, and most of those measurements derive from

relatively consolidated intervals. Observed and measured structures on cores are beddings, faults and deformation bands, mineral veins, and sediment veins. The precision of shipboard measurements equals that of terrestrial measurements in structural geology and accounts for numbers in the range of 1°–2° per single measurement. The accumulation of single measurements within groups of identified structures are concentrated around means typically giving confidence intervals with errors much smaller than for single measurements. Deformation related to drilling and core recovery was noted, but not recorded.

Planktic and benthic foraminifers, and calcareous nannofossils were examined from core catcher samples and additional split-core samples from Holes U1591A, U1591B, and U1591C to develop a shipboard biostratigraphic framework for Site U1591. Additionally, benthic foraminifers provided data on paleowater depths, downslope reworking, and possible dissolution. Site U1591 cored the Christiana Basin sedimentary sequence and recovered a 902.59 m thick Holocene to possibly late Miocene sequence. Calcareous nannofossils and planktic foraminifers provided good resolution in the Holocene through early Pliocene sediments. Ages provided by benthic foraminifers were also consistent with those of planktic foraminifers and calcareous nannofossils.

The Stratigraphic Correlators' main activity focused on the correlation of Holes U1591A and U1591B to identify coring gaps and create a first, tentative splice between both holes. Following this, the focus shifted to the correlation of the small overlap between the deeper parts of Hole U1591B and the uppermost cores of Hole U1591C. The majority of the work done by the Stratigraphic Correlation group, however, was on remodeling seismic velocities based on *P*-wave analyses from the Physical Properties group. The new seismic models informed our drilling strategy for the deeper parts of Hole U1591C.

Physical properties at Site U1591 are well correlated with lithology. Thick volcaniclastic layers in Unit I (ash, lapilli-ash, and lapilli) sometimes have low grain densities in coarse, pumice-rich subunits. Volcaniclastic deposits also exhibit large variations in magnetic susceptibility (MS) and often have high MS compared to other sediments at this site. High MS anomalies are most abundant and largest in amplitude at depths shallower than 490 mbsf. Unit II, which is dominated by nannofossil-rich oozes, often displays cyclic variations in natural gamma radiation (NGR) that are correlated with organic-rich layers. The evaporitic layers of Unit III have much higher *P*-wave velocity, thermal conductivity, and bulk density, and lower NGR, than the surrounding sediments.

To determine the geochemistry of the volcanic and tuffaceous materials, 20 tephra and ash samples were hand-picked from various layers within Holes U1591A, U1591B, and U1591C. Following cleaning, grinding, fusion, and dissolution, the materials were analyzed shipboard for major (Si, Al, Fe, Mg, and Ca), minor (Ti, Mn, Na, K, and P), and trace (Sc, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Ce, and Nd) elements using inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Of the volcaniclastic units sampled, three were classified as basaltic andesites, five as andesites, and twelve as dacites. Bulk chemistry values are less

evolved than glass chemistry, as expected due to bulk analyses including both minerals and glass. Concentrations are reported for all analyzed trace elements, but Ce, Cr, Cu, Nb, Ni, P, Rb, S, and V were below detection limits in the majority of samples. Trace element ratios were used to broadly discriminate between the volcanic centers of Kolumbo, Santorini, and Christiana.

To determine the inorganic constituents of interstitial water (IW), a total of 55 water samples were taken from the mudline and whole-round squeezing of sediment intervals at Site U1591 in Holes U1591A (10 samples), U1591B (12 samples), and U1591C (33 samples). Aliquots of IW were used for shipboard analyses, and the remaining water was taken for shore-based analysis, following protocols specified by individual scientists. The retrieved pore waters were analyzed shipboard for salinity, alkalinity, pH, major anions (Cl^-, SO_4^{2-}, and Br^-), major cations (Ca^{2+}, Na^+, Mg^{2+}, and K^+), and major (S, Ca, Mg, K, and Na) and minor (B, Ba, Fe, Li, Mn, P, Si, and Sr) elements.

Headspace gas analyses were performed at a resolution of one sample per full-length core (9.5 m advance) or one sample every other core for half-length cores (4.7 m advance) throughout Holes U1591A and U1591B. The aim was to monitor the presence and abundance of C1–C3 hydrocarbons as part of the standard IODP safety protocol. A total of 10 (Hole A) and 26 (Hole B) headspace gas samples were analyzed by gas chromatography (GC). Methane is the dominant hydrocarbon present with low methane concentrations or concentrations below the detection limit of Hole U1591A. Ethane, propane, butane, and other heavier hydrocarbons are either low or below the detection limit. Headspace gas analyses were resumed on Hole U1591C when a depth was reached that was deeper than that of Hole U1591B, which occurred at 389.9 mbsf. Below this depth, 53 headspace gas analyses were performed at a resolution of one sample per core to the base of the hole. Methane values were low until 559 mbsf where a gradual increase is observed until 612 mbsf where the maximum value of 883 ppmv is reached that is still well within safe operational margins. Below this depth, methane values decrease to 868 mbsf where values again increase to 168 ppmv. Ethane concentrations are low or below the detection limit except in intervals with elevated methane concentrations.

Paleomagnetic analyses at Site U1591 focused on the measurement and demagnetization of archive section halves to determine magnetostratigraphic ages controls. The topmost part of the sequence sampled at this site carries normal polarity remanences acquired during the Brunhes chron. Scattered inclinations then prevent magnetostratigraphic correlations from ~170 to 480 mbsf. Below this depth, however, the quality of data improves, and eight reversal boundaries can be tied precisely to the geomagnetic polarity timescale, with a further four tentative correlations also possible. Data in the evaporite sequence are less conclusive, however. Some intervals display reversed polarities consistent with known formation during reversals, but other intervals appear to be contaminated by a strong drilling-induced overprint with steep positive inclinations.

Due to the instability of the formations encountered, downhole logging was not conducted at Site U1591.