IODP Expedition 398: Hellenic Arc Volcanic Field

Site U1599 Summary

Background and Scientific Objectives

Site U1599 is located ~6 km north of Anafi Island within the upper reaches of the Anafi Basin in a water depth of 591 meters below sea level (mbsl). The site is complementary to Site U1592, in the Anafi Basin. It was drilled at three holes (Holes U1599A, U1599B and U1599C) to a maximum penetration depth of 697.8 meters below seafloor (mbsf) with average hole core recoveries ranging from 51% to 83%.

Site U1592 was situated on the axis of the Anafi Basin and penetrated a thick basin fill, including mass transported material. In contrast, Site U1599 is located on the southeast margin of the basin. It was chosen to offer a condensed sequence of tephra without the quantities of mass wasting debris. As such it would potentially provide a complete stratigraphy of volcanic tephra from Santorini and Kolumbo. The same six seismic units, U1 to U6, present at Site U1592 are present at Site U1599.

Drilling at Site U1599 would enable us to reconstruct a near-complete volcanic stratigraphy consistent with both onshore and offshore constraints and pinned by chronological markers from biostratigraphy, magnetostratigraphy, and astronomically tuned sapropel records. Benthic foraminifers from fine-grained sediments could provide estimates of ancient water depths and, via integration with seismic profiles and chronologic data, of time-integrated basin subsidence rates. Drilling in the Anafi Basin addressed science Objectives 1–4 and 6 of the Expedition 398 *Scientific Prospectus*. It is complemented by Site U1589 in the Anhydros Basin because each basin taps a different sediment distributary branch of the Christiana-Santorini-Kolumbo volcanic system.

Operations

The crew made-up the advanced piston corer/extended core barrel (APC/XCB) bottom-hole assembly (BHA) with bit. The BHA was run in to 585.7 meters below rig floor (mbrf). On 26 January 2023, following 12.75 h of awaiting national clearance approval for the site, the vessel attempted to spud Hole U1599A beginning at 1315 h. The APC was fired from 599.0 mbrf. Once retrieved, it was discovered the core barrel had parted at the mid connection. The pipe tally and the precision depth recorder (PDR) value were verified. A second attempt was made with the APC, unfortunately with the same result—a parted core barrel.

An XCB barrel was dropped and Hole U1599A (36°26.9592′N, 25°46.8005′E) was spudded at 1535 h with a solid tag at 602.5 mbrf. The barrel had no recovery, but it was obvious the coring

system had penetrated the seafloor. The half-length advanced piston corer (HLAPC) was deployed for Core 2F from 9.7 mbsf and had 97% recovery. Based on the recovery and sediment, it was assumed there was a tightly-compacted layer at the mudline preventing piston coring.

Coring was switched to APC with Cores U1599A-3H to 9H to a depth of 71.4 mbsf. The formation stiffened quickly, and the HLAPC was deployed for Cores 10F to 44F. Core 44F required a drillover and 100,000 lb overpull to release the barrel from the formation. The decision was made to terminate the hole at a final depth of 245.4 mbsf. The string was pulled up and the bit cleared the seafloor at 2145 h on 27 January, ending Hole U1599A.

The vessel was offset 50 m northeast of Hole U1599A. The seafloor was tagged at 604.0 mbsf. Hole U1599B (36°26.9764′N, 25°46.8237′E) was spudded at 2330 h on 27 January with Core U1599B-1X drilled to 9.7 mbsf. Coring was switched to the APC for Cores 2H to 11H, at 95.2 mbsf. High overpulls were observed on Cores 10H and 11H, and the HLAPC was deployed for Cores 12F to 40F (95.2–241.0 mbsf). The final depth for Hole U1599B was 241.0 mbsf. The drill string was tripped up, with the bit clearing the seafloor at 0100 h on 29 January and clearing the rotary table at 0255 h. The drill floor was secured for transit and the thrusters were raised starting at 0324 h. All thrusters were up and secure, the vessel was under bridge control, and the sea passage to Site U1600 started at 0336 h.

The vessel returned to Site U1599, and Hole U1599C (36°26.9389′N, 25°46.7762′E) was spudded on 30 January at 1925 h. A seafloor depth of 604.0 mbrf was used and the hole was advanced without recovery to 223.0 mbsf. Rotary core barrel (RCB) coring commenced from Core U1599C-2R to 25R to 455.5 mbsf. The drill string was tripped from 455.5 to 55.6 mbsf.

The rig crew pulled the upper guide horn (UGH) in preparation for launching a free-fall funnel (FFF). The FFF was assembled and welded in the moonpool. The FFF was launched at 2005 h on 1 February and was immediately followed with the vibration isolated television (VIT) camera at 2015 h. Once at the seafloor, the VIT camera verified the FFF had landed successfully. The pipe was tripped out of the hole from 55.6 mbsf to 516.7 mbrf, with the camera observing. The bit cleared the seafloor at 2117 h and seemed to leave the FFF undisturbed. The VIT was back on deck at 2209 h. The rig crew then reinstalled the UGH and reassembled the rig floor. The bit cleared the rotary table at 0025 h. The rig floor was secured, the vessel switched to bridge control, and the sea passage to Site U1595 began at 0142 h on 2 February, ending Site U1599 for the time being.

After returning to the site on 5 February, the crew made-up the RCB BHA. Winds were forecast to rise above 40 kt, with gusts over 50 kt, exceeding shallow operations limits. The vessel began waiting on weather (WOW) with the pipe down, beginning at 0915 h on 6 February. The ship was offset 5.5 nm west of Site U1599 in dynamic positioning (DP) mode to deeper water, away from the isle of Anafi.

At 1840 h on 6 February, in anticipation of the weather and sea state improving, the ship started the DP move back over Hole U1599C. The move was completed at 0100 h on 7 February. The VIT was deployed and the vessel was maneuvered for reentry for about 30 min, reentering Hole U1599C at 0230 h. The VIT was retrieved and back on deck at 0345 h. The pipe was tripped to 56.6 mbsf and the top drive was assembled. The trip in progressed to 455.5 mbsf.

At 1300 h on 7 February, RCB coring continued from Core U1599C-26R to 50R (455.5–697.8 mbsf). The drill string was pulled from the hole with the bit clearing the rotary table at 2030 h on 9 February. The rig floor was secured with all equipment put away at 2130 h. The thrusters were raised and the vessel was brought under bridge control at 2134 h. All thrusters were up and secure, with the start of the sea passage to Heraklion at 2142 h on 9 February marking the end of Site U1599.

Principal Results

Cores from Site U1599 recovered a relatively coherent stratigraphy from 0 to 697.8 mbsf. Lithostratigraphic Unit I consists of mixed volcanic, tuffaceous, and nonvolcanic material in the upper ~220 m, which transitions to dominantly ooze interspersed with minor volcanic and tuffaceous sediments for the following ~25 m (lithostratigraphic Unit II). Lithostratigraphic Unit III consists of ~300 m dolomitic marl with organic-rich dominated intervals, followed by ~144 m of micrite and calcareous sandstones (lithostratigraphic Unit IV). Smear slides for microscopic analyses were prepared to confirm macroscopic descriptions of distinct lithology changes at the section level, such as identification of vitric particles in tuffaceous lithologies, or crystals in ash layers.

Within Unit I, four subunits were identified based on the amount of volcanic, tuffaceous, or nonvolcanic sediments. These subunit distinctions are corroborated by physical property data, i.e., magnetic susceptibility (MS) and natural gamma ray (NGR). Units II and IV do not exhibit sufficient variation to warrant subunits. Unit III, an organic-rich lithology, is divided into Subunits IIIa, IIIb, and IIIc. X-ray diffraction (XRD) data were obtained from 21 interstitial water (IW) squeeze cake sediment residues from Hole U1599A, two IW squeeze cake sediment residues from Hole U1599B, and 16 IW squeeze cake sediment residues from Hole U1599C. Additionally, two further samples from Hole U1599C were analyzed by XRD.

A total of 625 structures were measured, and most of those measurements come from relatively consolidated intervals. Observed and measured structures on cores are beddings, faults and deformation bands, mineral veins, and a sand dyke (injection). Where possible, we corrected the measurements of planar and linear structures to true geographic coordinates using paleomagnetic data. The precision of shipboard measurements equals to that of terrestrial measurements in structural geology and accounts to numbers in the range of 1°–2° per single measurement. 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 U1599A to U1599C to develop a shipboard biostratigraphic framework for Site U1599. Additionally, benthic foraminifers provided data on paleowater depths, downslope reworking, and possible dissolution. Calcareous nannofossils and planktic foraminifers provided good resolution in the Holocene through upper Pliocene sediments; however, significant reworking within the lower section required the use of first occurrence datums for primary age control. Ages provided by benthic foraminifers were also consistent with those of planktic foraminifers and calcareous nannofossils.

To establish the composite depth scale, Holes U1599A–U1599C were analyzed for their physical properties using the Whole-Round Multisensor Logger (WRMSL) for MS and gamma ray attenuation (GRA), and the gamma ray track (for NGR intensity), as well as core photos. The MS data were the most reliable physical parameter for correlations, while NGR and GRA density measurements were often overprinted by the irregular distribution of core material in cores with low recovery and a high content of water. Because the mudline was not preserved, we used Core U1599A-2F as the anchor for stratigraphic correlation. Using this anchor core, we attempted to determine the relative depth offset of each core by establishing affine ties between the holes based on the maximum correlation of all measured physical properties.

In general, reliable correlations were identified between most cores of Holes U1599A and U1599B until a depth of ~160 mbsf. Below this, low recovery, as well as strong lithological variations and a soupy nature of the recovered material, led to gaps in the stratigraphic correlation. For each of these interruptions, the relative offset between untied (noncorrelated) cores derived from the core depth below seafloor, Method A (CSF-A) scale was used to keep the composite depth scale as close to the original CSF-A scale as possible.

Once the composite depth scale was established, selected sequences from Holes U1599A and U1599B were spliced, and the additional, but sparser, parts of Hole U1599C were added together to create the most complete and representative section possible.

There is a general trend of increasing *P*-wave velocity, bulk density, and thermal conductivity with increasing depth at Site U1599. MS is highly variable in volcaniclastic layers of Units I and II and is sometimes very high. The dolomitic marls of Unit III have low MS, and *P*-wave velocity increases systematically with increasing depth, except for a sandy interval where *P*-wave velocity decreases slightly before increasing more gradually with increasing depth. In the micrites of Unit IV, MS is higher than in Unit III and *P*-wave velocity increases with increasing depth.

Sediment strength was measured with a pocket penetrometer on the catwalk immediately after section splitting. Automated vane shear (AVS) measurements were made on working half sections. A total of 22 and 7 AVS measurements were made on working half sections in Holes U1599A and U1599B, respectively. A total of 22 and 25 pocket penetrometer measurements were made on fine-grained materials that remained intact in core liners upon recovery on the

catwalk in Holes U1599A and U1599B, respectively. There is a general trend of increasing shear strength with increasing depth, and the magnitudes of the AVS and pocket penetrometer measurements are similar in the upper 150 mbsf.

A total of 651, 616, and 1852 discrete *P*-wave velocity measurements were conducted on the Hole U1599A, U1599B, and U1599C working half sections, respectively. Discrete measurements of *P*-wave velocity on working half core sections from Holes U1599A and U1599B are similar to those measured by WRMSL measurements on whole-round cores.

To determine the geochemistry of the volcanic and tuffaceous materials, nine tephra samples were handpicked from various layers within Hole U1599A. 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, one was classified as a basalt, one as an andesite, and seven as dacites. 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 discriminate broadly between the volcanic centers of Kolumbo, Santorini, and Christiana.

To determine the inorganic constituents of IW, a total of 44 water samples were taken from the mudline and whole-round squeezing of sediment intervals at Holes U1599A (21 samples), U1599B (2 samples), and U1599C (15 samples). Of the 44 samples, 38 aliquots of IW were used for shipboard analyses, and the remaining water was taken for shore-based analysis, following protocols specified by individual scientists. An additional six samples were processed for shore-based analysis only. 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) throughout Holes U1599A and U1599C. The aim was to monitor the presence and abundance of C1–C3 hydrocarbons as part of the standard IODP safety protocol. A total of 71 headspace gas samples were analyzed by gas chromatography (GC). Methane, ethane, and propane concentrations are below the detection limit through all of Hole U1599A. Methane concentrations in Hole U1599C increased between 266 and 311 mbsf, reaching a maximum of 816.3 ppmv at 275.7 mbsf. Methane, ethane, and propane concentrations were below the detection limit in all other samples.

Paleomagnetic analysis at Site U1599 focused on measurement and demagnetization of archive section halves to determine magnetostratigraphic age controls. Three reversal boundaries could be tied with confidence to the geomagnetic polarity timescale (GPTS) as follows: (i) the Brunhes–Matuyama transition (0.773 Ma); (ii) the top of the Jaramillo subchron (1.008 Ma); and (iii) the base of the Jaramillo subchron (1.076 Ma).

Microbiological analysis was conducted on 35 whole-round samples from Site U1599. The whole-round samples were split into 246 subsamples. Most of the microbiological analyses will be conducted on shore, but first culturing experiments indicate the presence of the iron oxidizing bacterium *Mariprofundus ferroxydans*.

Due to the instability of the formations encountered, downhole logging was not conducted at Site U1599.