IODP Expedition 392: Agulhas Plateau Cretaceous Climate

Site U1580 Summary

Background and Objectives

Site U1580 (proposed Site AP-09B) is located on the southern central Agulhas Plateau (40°47.1535′S, 26°36.4137′E) in 2560 m water depth. The site lies about 100 km southeast of Site U1579. Bathymetric data show Site U1580 is located on the flank of a high. This bathymetric high is underlain by a number of basement highs as revealed by seismic data. A rugged topography characterizes the top of the interpreted basement. Below this horizon, reflections have been observed dipping away from the basement highs in all directions. The basement highs have thus been interpreted as extrusion centers. The seismic data show a chaotic layer topped by reflector M with a strong reflection amplitude. Another strong seismic horizon can be observed, reflector LE. Both reflectors M and LE follow the basement topography. The sequence above reflector LE shows parallel to subparallel continuous reflections of middle to strong amplitude. The youngest part of this sequence is affected by erosion at the seafloor.

Site U1580 was chosen to recover both Cretaceous and Paleogene sedimentary records and basement samples. This site was especially dedicated to recover an extended record of basement material to unravel the nature of the basement and provide information on its formation age. Potential late stage magmatism and the effect on sedimentary sequences and the environment form additional objectives. Integration of seismic profiles with the drilling results will allow direct dating of the observed seismic unconformities and interpretation of their causes, and recovery of the sediment/basement interface will provide information on the age of the oldest sediments on crust, the palaeodepth, as well as paleoenvironment. At this site, a sediment sequence from the mid-Cretaceous to mid-Paleogene was expected to be drilled, spanning the long-term climate transition from the Cretaceous greenhouse to the mid-Paleogene icehouse. Critical intervals of ocean/climate transitions such as Oi-1 glaciation, the Paleocene/Eocene Thermal Maximum (PETM), Cretaceous/Paleogene (K/Pg) boundary, Oceanic Anoxic Event (OAE) 2, and OAE 3 were expected to be documented in the sedimentary record. The nature and age of the basement would also be unraveled by drilling at this site.

Operations

The vessel arrived at Site U1580 at 1306 h on 25 February 2022. All times are local ship time (UTC + 2 h). The thrusters were lowered and the vessel switched from cruise mode to dynamic positioning (DP) mode at 1326 h. Hole U1580A was spudded with Core U1580A-1R at 2015 h, recovering 6.82 m. For the next several days, rotary core barrel (RCB) coring continued through Core 42R, advancing from 9.7 to 407.4 m and recovering 250.38 m (63%).

At ~1700 h on 1 March, the rate of penetration (ROP) on Core U1580A-43R slowed to almost zero and no noticeable progress was being made. Following an additional short advance with no recovery in Core 44R, the bit deplugger (a core barrel with a pointed metal tip) was dropped twice in an attempt to clear any material blocking the bit. Core 45R then advanced 3.2 m and recovered 3.25 m. It was determined from recovered pieces that a chert layer of loosened rock was slowing the ROP and preventing recovery.

The sediment/basement contact was very difficult to determine during coring, likely due to multiple chert/silicified horizons in the sediments immediately overlying the basalts. Although core recovery was low, pieces of basalt were recovered in Cores U1580A-43R and 45R, and a good basalt contact was cored at ~419–420 m cored depth below seafloor (CSF-A) in Core 47R on 2 March. Coring in Hole U1580A continued until 1630 h on 5 March with a final hole depth of 533.9 m CSF-A. The basalt below ~495 m CSF-A cored at a ROP of 3–5 m/h, which is very fast for hard rock, and with good recovery. The overall ROP for RCB in Hole U1580A was 4.4 m/h.

At 1630 h on 5 March, the driller pumped a final sweep to clean the hole, flushing the mud completely out of the hole. The mechanical bit release (MBR) tool was run down, and the bit dropped at 1715 h. The drill string was tripped up to 80.7 m CSF-A in preparation for downhole logging. At 2145 h the first logging string, the triple combo, was assembled. The triple combo consists of the Hostile Environment Natural Gamma Ray Sonde (HNGS), Hostile Environment Litho-Density Sonde (HLDS), and Magnetic Susceptibility Sonde (MSS). The triple combo continued logging down to a tag depth of 524.2 m CSF-A. The logging run was completed and the tool was out of the hole at 0630 h on 6 March. For the next downhole logging run, the Formation MicroScanner (FMS)-sonic suite was assembled and deployed at 0900 h. The FMS-sonic tool consists of the Dipole Shear Sonic Imager (DSI) and FMS. Two passes were conducted, with both tags at ~521.5 m CSF-A. The tools were back at the surface at 1535 h. For the final downhole logging run, the Ultrasonic Borehole Imager (UBI) consisted of the General Purpose Inclinometry Tool (GPIT) and UBI.

The UBI tool was run-in hole at 1610 h. One pass was completed to 504.5 m CSF-A. The second pass was aborted after difficulties with the tool, and it was later determined that the transducer subassembly motor was sticking. The UBI logging run was completed with the tools at the surface at 0020 h on 7 March. The drill pipe cleared the rig floor at 0705 h, ending Hole U1580A. A total of 68 cores were taken in Hole U1580A over a 533.9 m interval with 65.7% recovery. Total time on Hole U1580A was 232.8 h (9.7 d).

A new C-4 RCB bit was prepared, and after lowering the drill pipe to near the seafloor the vessel was offset 20 m east. An RCB with center bit was installed and Hole U1580B was spudded at 1710 h from a seafloor depth of 2571.5 meters below rig floor (mbrf). The hole was drilled to 40.0 m CSF-A, and we used the RCB system to take Cores U1580B-2R through 5R (to 77.8 m CSF-A). Drill pipe was tripped back to the ship and cleared the rig floor at 1430 h, ending Hole U1580B. The ROP for RCB coring averaged 7.2 m/h and the 40 m drill down averaged 14.6

m/h. A total of 4 cores were taken in Hole U1580B over a 37.8 m interval with 62.9% recovery. Total time on Hole U1580B was 31.2 h (1.3 d).

Principal Results

Lithostratigraphy

Site U1580 consists of a 528.58 m sequence of calcareous and siliciclastic sediments and basalt. Basalt and sediments are interbedded in the lowermost ~120 m of the section. Fourteen lithostratigraphic units are defined, with Units II and III being further subdivided into five subunits (IIa, IIb, IIc, IIIa, and IIIb). Units I–III, V, VII, IX, XI, and XIII are largely composed of calcareous chalks and siliciclastic sandstones, siltstones, and claystones, whereas Units IV, VI, VII, X, XII, and XIV are basalt.

Lithostratigraphic Unit I (0.00–3.42 m CSF-A) consists of light gray to light brown foraminiferal ooze with nannofossils. The lower contact Unit I with Unit II at 3.42 m CSF-A, however, is severely deformed by drilling disturbance, but is marked by a downcore change to white nannofossil ooze below the contact. Lithostratigraphic Unit II is a ~290 m thick sequence of Eocene–Santonian nannofossil ooze and chalk that is subdivided into three subunits (Subunits IIa–IIc). Subunit IIa (3.42–16.73 m CSF-A) is 13.31 m thick and is characterized by massively bedded white or pale yellow to light greenish-gray nannofossil ooze. Subunit IIb (19.40–207.11 m CSF-A) consists of ~188 m of white to light greenish-gray nannofossil chalk and differs from the overlying Subunit IIa in being a more lithified chalk (vs. ooze in the overlying subunit) and having higher carbonate content. Subunit IIc (207.11–293.51 m CSF-A) is 86.40 m thick and consists of light greenish-gray calcareous chalk with cyclic bands of greenish-gray or reddish-brown clayey calcareous chalk, with occasional chert layers. The boundary between Subunits IIb and IIc is associated with an increase in magnetic susceptibility (MS) and natural gamma ray (NGR) values between ~200 and 220 m CSF-A. Carbonate content in Subunit IIc is generally high (~80%–95%); however, it is more variable than in Subunits IIa and IIb, which likely reflects lower carbonate content in the brown and green clay-rich intervals. The K/Pg boundary occurs in Subunit IIc between 207.10 and 211.44 m CSF-A within an interval characterized by intense bioturbation and alternating bands of darker reddish-brown clayey nannofossil chalk and lighter greenish-gray nannofossil chalk with clay.

The contact between Lithostratigraphic Units II and III at 293.51 m CSF-A is marked by a gradational change from reddish-white calcareous chalk to green zeolitic clastic sediments, corresponding to a notable decrease in carbonate content and a sharp increase in MS, drop in thermal conductivity, and increase in porosity. Unit III is 113.96 m thick and subdivided into two subunits (Subunits IIIa and IIIb). Subunit IIIa (293.51–349.98 m CSF-A) is characterized by green zeolitic sandstones, siltstones, and claystones, with more sporadic occurrences of calcareous microfossils and lower carbonate content relative to overlying units. Subunit IIIb (349.98–407.46 m CSF-A) is composed of light green, dark green, and light red calcareous

sandstones, siltstones, and claystones. The light green intervals of Subunit IIIb are calcareous chalk and contain common to abundant calcareous microfossils as well as carbonate mineral grains.

The first downcore occurrence of igneous rocks in Hole U1580A is at 407.46 m CSF-A, defined as the top of Lithostratigraphic Unit IV. The contact between Subunit IIIb and the underlying basaltic Lithostratigraphic Unit IV was not recovered. Below this level, sediments in the lowermost ~120 m of the Site U1580 sequence are interbedded with basalts (see Igneous Petrology below), consisting of Lithostratigraphic Units V, VII, IX, XI, and XIII. Lithostratigraphic Unit V (411.76–412.82 m CSF-A) consists of bluish-gray to light reddish-gray, thinly laminated silicified limestone and chert. Unit VII (426.25–426.27 m CSF-A) is a thin ~2 cm thick interval of calcareous chalk that is bounded by basalt above and below, which preliminary downhole log analysis suggests may be representative of a sedimentary interval up ~1–2 m thick. Unit IX (438.97–439.49 m CSF-A) is a 52 cm thick interval of black chert that contains several white intersecting calcite veins. Unit XI (466.63–471.60 m CSF-A) consists of gray to black calcareous chalk, nannofossil-rich claystone, silicified limestone, and chert, including an interval of abundant inoceramid (bivalve) fragments. Unit XIII (478.53–490.54 m CSF-A), the lowermost sedimentary unit recovered at Site U1580, consists of mixed lithologies including greenish-gray, light brownish-gray, and gray calcareous chalk, black claystone, siltstone, and clayey calcareous chalk.

Igneous Petrology

A sequence of igneous units of varying thickness intercalated with sedimentary intervals was recovered in Lithostratigraphic Units IV–XIV in the lowermost ~120 m of Hole U1580A (407.46 to 528.58 m CSF-A). Coring of the igneous intervals in this sequence yielded excellent recovery rates averaging ~84%. All igneous rocks recovered at Site U1580 are classified as aphyric or slightly plagioclase and/or olivine phyric basalts, with 10 igneous units defined on the basis of differences in macro- and microscopic texture and identifiable contacts. Throughout the recovered basalts, olivine crystals, as phenocrysts or in the groundmass, are completely replaced by alteration phases (predominantly clay minerals) contributing to the overall moderate-to-high degree of alteration of these units. In addition to near continuous recovery of igneous successions, isolated basalt fragments were also recovered within primarily sedimentary intervals. For instance, Lithostratigraphic Unit XIII (478.53–490.54 m CSF-A), which mainly comprises calcareous chalk, claystone, and siltstone, also contains three unoriented pieces of basalt; these basalt cobbles are distinct from the igneous units above and below Unit XIII and likely represent a thin interval of basalt not coherently recovered at ~488 m CSF-A.

The intercalation of igneous bodies and sediment packages in Hole U1580A implies that these units represent either lateral intrusions (sills) or that they were emplaced as lava flows on which sediments were deposited after each eruption. Based on several lines of evidence, we interpret this igneous succession as sills. Sharp igneous contacts and broad chilled margins (without volcanic glass), slow gradational changes in crystallinity (grain size) toward coarsely crystalline

interiors and certain mineralogical textures (subophitic, doleritic) of the recovered units resemble sills rather than lava flows. Compelling evidence for sill intrusions into sedimentary deposits is also the thermal overprint or "baking" (contact metamorphism) of the adjacent sedimentary lithology as repeatedly observed in Hole U1580A. Similar reactions may also appear beneath thick lava flows, but would not be expected above a flow, since any sediments deposited on an already existing lava body should be of younger age.

Micropaleontology

The sedimentary intervals of the 525.58 m thick succession cored at Site U1580 contain calcareous nannofossils, foraminifers, siliceous microfossils, and palynomorphs in varying abundance and preservation state. Calcareous nannofossils are abundant and moderately to well-preserved in Paleogene and Pleistocene sediments (~0–205 m CSF-A), whereas abundance and preservation of calcareous nannofossils are more variable in Cretaceous sediments (~205 to 491 m CSF-A), with some samples barren of nannofossils and preservation generally poor to moderate. Despite variable preservation and abundance, nannofossils are present throughout the recovered sediment and provide excellent biostratigraphic control for the Paleogene and reasonably good control for the Cretaceous. Foraminifers are abundant and generally well-preserved in the upper part of Site U1580. Below ~115 m CSF-A, foraminiferal abundance decreases and preservation deteriorates, although in some intervals of poor preservation delicate morphological features such as test pore structures are preserved. Radiolarian fragments, as well as pyritized diatoms and radiolarians, were encountered in only a few samples from Site U1580. Trace numbers of palynofacies consisting of black phytoclasts are present in the Paleocene to lower Eocene sediments, whereas dinoflagellate cysts (dinocysts), miospores, and black phytoclasts are rare to abundant in the Cretaceous sediments, with some samples showing thermal alteration in the color of the palynomorphs.

Chronostratigraphy

Calcareous nannofossils, planktonic and benthic foraminifers, dinocysts, and magnetostratigraphy provide age control for the uppermost Cenomanian–lower Eocene sediment cores recovered at Site U1580. In the lowermost sequence of Site U1580, nannofossils constrain the age of sedimentary units interbedded with basalts (Lithostratigraphic Units XI and XIII; 466.63–490.54 m CSF-A) to the latest Cenomanian–earliest Turonian interval (~94 Ma). Sediments of Lithostratigraphic Unit III (~294–407 m CSF-A) overlying the basalts are dated to the Coniacian–Santonian interval (~84–88 Ma) using dinocyst and nannofossil biostratigraphy. Paleomagnetic results show continuous normal polarity through Lithostratigraphic Unit III due to deposition during the C34n Superchron.

Lithostratigraphic Unit IIc (207.11–293.51 m CSF-A) is age dated to the Campanian–early Maastrichtian interval on the basis of nannofossil biostratigraphy and magnetostratigraphy. Although several polarity reversals are preliminarily correlated to the geomagnetic polarity timescale (GPTS) in this interval, nannofossil biostratigraphy only provides broad age

constraints, and further higher resolution postcruise study is required. A hiatus is inferred at ~224 m CSF-A, truncating the lower Maastrichtian succession, with a duration of at least 2 My based on calcareous nannofossil biostratigraphy and magnetostratigraphy. The K/Pg boundary (~66 Ma) is identified in Core U1580A-22R between 209.09 and 211.44 m CSF-A.

Between ~63–210 m CSF-A, the Paleocene section of Site U1580 appears to be continuous at the resolution of 18 shipboard bio- and magnetostratigraphic (C24r through Chrons C29r; ~56–56 Ma) age tie points. The Paleocene/Eocene boundary is identified at 63.32 m CSF-A in Hole U1580A and 62.07 m CSF-A in Hole U1580B based on nannofossil biostratigraphy, a distinct color change, and physical properties. Seven foraminiferal and nannofossil biostratigraphic datums provide age constraints within the lower Eocene succession (3.42–63.32 m CSF-A), constraining the age to ~53.6–56 Ma. Due to low magnetization intensity, no magnetic reversals were identified in lower Eocene section of Site U1580. The uppermost sediments recovered at Site U1580 (Lithostratigraphic Unit I; 0–3.42 m CSF-A), which rest on a hiatal surface above the Eocene sediments below, are dated to the Pleistocene based on foraminiferal and nannofossil biostratigraphy.

Paleomagnetism

Paleomagnetic measurements were undertaken on all archive section halves of both Holes U1580A and U1580B, and on 68 discrete samples from Hole U1580A. Demagnetization experiments and rock magnetic analyses were also performed to constrain magnetic polarity and the magnetic mineralogy of the sedimentary and igneous units collected from Site U1580. Paleomagnetic results indicate that the units sampled at Site U1580 are reliable recorders of magnetic field direction. Magnetic polarity was determined from 61 of the 68 cores measured from Hole U1580A, and all four cores measured from Hole U1580B. Fifteen magnetic reversals were identified, and normal and reverse polarity intervals were correlated to chrons within the GPTS from the Geologic Time Scale 2020 (GTS2020) (Gradstein et al., 2020; Ogg, 2020). In combination with biostratigraphic results, these reversals were successfully correlated to the GPTS and span the top of Chron C25n to the top of Chron C33n (~57–74 Ma; Thanetian–Campanian).

Rock magnetic results from Site U1580 indicate that the dominant magnetic mineralogy is a combination of both ferrimagnetic and antiferromagnetic minerals, likely magnetite and hematite. Both ferrimagnetic and antiferromagnetic minerals occur within sedimentary Units I through IIc (~0 to 300 m CSF-A), which transitions to dominantly ferrimagnetic minerals in Lithostratigraphic Units III through Unit XIV (~300 to 530 m CSF-A). Measurements of the anisotropy of magnetic susceptibility indicate that sedimentary units recovered at Site U1580 possess a typical oblate sedimentary fabric and that the basalts lack strong magnetic fabrics.

Stratigraphic Correlation

At Site U1580, two holes were RCB cored, Hole U1580A to a depth of 533.9 m drilling depth below seafloor (DSF), with the deepest depth recovered at 528.58 m CSF-A, and Hole U1580B from a depth of 40.0 m DSF to a depth of 77.8 m DSF, with the deepest depth recovered at 74.14 m CSF-A. Within the interval where the stratigraphy of the holes overlapped (from Core U1580A-5R to 8R, 38.80 to 72.82 m CSF-A, and from Core U1580B-2R to 5R, 40.00 to 74.14 m CSF-A), recovery was 68% in Hole U1580A and 63% in Hole U1580B. Core breaks aligned between Holes U1580A and U1580B, and Cores U1580A-5R to 8R and Cores U1580B-2R to 5R showed signs of drilling disturbance, hampering the construction of a splice. Compiled records of the cored intervals at Site U1580 demonstrate 66% recovery of the drilled interval spanning sediments of late Cenomanian to early Eocene age, as well as igneous rocks. A core composite depth below seafloor (CCSF) depth scale is provided for Hole U1580A to enable visualization of results without overlap of recovered intervals between cores.

Geochemistry

The geochemistry program at Site U1580 was designed to characterize the composition of bulk sediment and interstitial water (IW) and diagnose the abundance of volatile hydrocarbons for routine safety monitoring. Methane above the detection limit was not found in any samples. Traces of propene (17.35 ppmv), iso-pentane (5.75 ppmv), iso-hexane (3.87 ppmv) and h-hexane (2.12 ppmv) were detected in Sample U1580A-9R-7, 0–5 cm (86.63 m CFS-A).

IW samples were analyzed in Hole U1580A down to 356.16 m CSF-A, below which pore water was not extractable. Pore water alkalinity, pH, and major anion and cation concentrations all show distinctive downhole trends. Alkalinity values decrease from roughly 2.9 mM at the top of the sedimentary sequence to 0.3 mM at 311.27 m CSF-A. pH values are relatively constant with values of 7.4 to <7.7 throughout the upper 185 m CSF-A, which increase to 7.7–8.3 below 295 m CSF-A. Of the major anions, sulfate decreases from a value of ~28 mM at 3.75 m CSF-A to a value of ~22 mM at ~356 m CSF-A, and chloride increases downhole from 573 mM to values exceeding 600 mM below ~300 m CSF-A. The major cation sodium shows a slight decline from its seawater value (481 mM) in the upper part of the hole to a depth of ~328 m CSF-A, below which values decline to 452 mM at 356.16 m CSF-A. Calcium increases from ~10.7 mM at 3.75 m CSF-A to a concentration of 86.1 mM at ~343 m CSF-A. Magnesium inversely mirrors the calcium values and declines from 51.3 mM at 3.75 m CSF-A to 3.1 mM at 343.81 m CSF-A. Potassium notably declines downhole from 11.78 mM at 3.75 m CSF-A to 1.16 mM at 343.81 m CSF-A.

In total 83 sediment samples from Site U1580 were analyzed for bulk carbon and nitrogen analyses down to 485.99 m CSF-A. Total carbon and $CaCO_3$ weight percentages range from 0% to 14.5% and 0% to 97% at Site U1580, respectively, which is consistent with the deposition of pelagic nannofossil oozes and chalks, zeolitic sand/siltstones, limestone, and claystone. Average total organic carbon is 0.64% ± 0.27% with minimum and maximum concentrations of 0% and

9.34%, respectively. Five samples with total organic carbon (TOC) content exceeding 1% are below ~315 m CSF-A, with two samples exceeding 5% in the lowest part of the core deeper >410 m CSF-A composed of calcareous siltstone and black claystone.

Samples from nine representative sills drilled at Site U1580 were selected for inductively coupled plasma–atomic emission spectroscopy (ICP-AES) analyses. Based on classic discrimination diagrams for igneous rocks, all three samples classify as tholeiitic basalts, plotting along with tholeiitic lavas from the neighboring Mozambique Ridge and the only hitherto available basement (dredge) samples from the Agulhas Plateau.

Physical Properties

Physical properties of sediments and igneous rocks recovered at Site U1580 were measured on whole-round core sections, split half core sections, and discrete samples to a total depth of 528.58 m CSF-A in Hole U1580A. Complementary downhole logging datasets were also collected from Hole U1580A. Between ~40 and 74 m CSF-A, cores from Hole U1580A and Hole U1580B overlap stratigraphically. Measured variations in physical properties arise from lithification with increasing burial depth and from variations in lithological composition. The upper part of the section shows small variations in MS, NGR, *P*-wave velocity, and density (Lithostratigraphic Unit I and Subunits IIa and IIb; 0 to ~208 m CSF-A). The overall higher *P*-wave velocities and densities and color change towards darker and more reddish layers in the lower part of Lithostratigraphic Subunit IIb (~19.4 to 207.11 m CSF-A) are attributed to diagenetic changes and to an increase in clay content. Anomalous physical properties downcore were recorded in the zeolitic sandstone, siltstones, and claystones of Lithostratigraphic Subunit IIIa (293.51–349.98 m CSF-A), characterized by a decrease in bulk density, increase in porosity, low *P*-wave velocities down to ~2000 m/s, and a sharp drop in thermal conductivity compared to the strata above and below. Increased MS and NGR values also correlate with the zeolitic sediments of Lithostratigraphic Unit III (~293.51 to 407.46 m CSF-A). Deconvolved Natural Gamma Radiation Logger (NGRL) spectral data indicate that potassium is enriched to ~0.5–2.0 wt% in the zeolitic sandstones to claystones of Unit III, likely reflecting an increase in authigenic minerals rich in potassium such as glauconite and celadonite. Exceptional peaks in NGR (related to high uranium content) were also observed in a few dark layers in Cenomanian-Turonian deposits (Lithostratigraphic Unit XII; ~471.6 to 478.53 m CSF-A) sandwiched between basalt layers (Lithostratigraphic Units XI and XIII).

Downhole Measurements

Downhole measurements at Site U1580 consisted of wireline logging of Hole U1580A on 5 and 6 March. No downhole temperature data were measured at this site. In addition to standard sonic and MS data, high-resolution density, NGR, neutron porosity, electrical resistivity, FMS, and UBI imagery provided a continuous borehole record, documenting lithologies of unrecovered stratigraphic intervals where coring gaps occurred in Hole U1580A. Downhole gamma ray spectroscopy data indicate that sediments of Lithostratigraphic Units II and III occupy two

distinct compositional domains of potassium/thorium ratios. The potassium-rich Unit III is characterized by anomalously high porosity (>60%) which is confirmed by the moisture and density (MAD) analysis. The integrated interpretation of downhole data is instrumental to identify the true thickness of sediments and nature of their contacts with basalts below 407 m wireline log matched depth below seafloor (WMSF). The UBI and FMS images display various degree of alteration/fracturing in basalts and sharp transitions to the interbedded sediments. The sedimentary rocks sandwiched within basalt units are characterized by elevated uranium content with peaks at about 2 ppm. The cross-dipole setup of acoustic logging enables a detailed core-to-seismic integration including the analysis of elastic anisotropy.

References

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