IODP Expedition 392: Agulhas Plateau Cretaceous Climate

Site U1579 Summary

Background and Objectives

Site U1579 (proposed Site AP-10A) is located on the shallowest part of the central Agulhas Plateau (39°57.0725´S, 26°14.1793´E) in 2492 m water depth. The Agulhas Plateau rises up to 2200 m above the surrounding seafloor, with the shallowest central region rising to ~1800 m on average. The central and southern parts of the plateau show a smoother topography, while the northern plateau is characterized by a rough topography. The sedimentary column is thicker on the central and southern Agulhas Plateau while the northern plateau shows a very thin or no sedimentary cover. Basement highs characterize the plateau and have been interpreted to represent magmatic edifices. The plateau has been subject to erosion resulting in wedge-out of sequences and the formation of unconformities, which are interpreted to have resulted from oceanic currents flowing across and past the plateau since the Paleogene. The seismic data show that Site U1579 is positioned between two basement highs in a small sediment-filled depression. The seismostratigraphic model developed prior to drilling provides a framework for interpreting the drillcore results. The deepest horizon interpreted is characterized by a rugged topography and has been interpreted as top of basement. Below this horizon, reflections have been observed dipping away from the basement highs. The sedimentary column shows a chaotic layer with a strong top reflection immediately above basement. Two further strong seismic horizons can be observed separating layers of potentially Campanian, Maastrichtian, and Paleocene age. These reflections and the Campanian and Maastrichtian sequences follow the basement topography. The younger sequences show continuous reflections of weaker amplitude. The youngest part of the sedimentary column is affected by strong erosion at the seafloor.

Site U1579 was chosen to recover both Cretaceous and Paleogene sedimentary records and basement samples. 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, paleodepth, and paleoenvironment of the oldest sediments above basement. At this site, records spanning the transition from the Cretaceous Supergreenhouse and through the Paleogene were to be drilled. Critical interval of ocean/climate transitions such as the 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

Expedition 392 started on 5 February 2022, and following quarantine the science party boarded on 7 February under the COVID Mitigation Protocols Established for Safe JR Operations

(COPE). All times are local ship time (UTC + 2 h). The majority of incoming freight was loaded by the previous crew, and on 8 February the offgoing core and surface freight was loaded into two reefers. Fuel bunkering was done via barge and a load of fresh and frozen produce was brought onboard. The final installation, testing, and commissioning of the new 50 kVA uninterruptable power supply (UPS) for the JRSO network was done on 8 and 9 February, requiring temporary blackouts of shipboard IT services. COVID-19 rapid antigen testing was conducted for all shipboard personnel on 8 February and PCR testing was conducted on 9 February.

The vessel departed Repair Quay 3 on 10 February at 1024 h. The pilot disembarked at 1045 h, beginning the sea voyage to Site U1579. Within minutes of the vessel reaching full throttle, the newly commissioned 50 kVA UPS began rejecting the ship's power and running off the batteries, thus the vessel was throttled back to half speed at 1116 h. It was decided to take the UPS offline, after which the vessel was returned to full throttle at 1448 h, and the sea voyage continued at full speed. The 557 nmi transit was completed in 52.1 h at an average speed of 10.8 kt. We arrived at Site U1579 at 1430 h on 12 February.

The first core of Expedition 392 was taken in Hole U1579A at 0500 h on 13 February in 2498.32 m of water. We used the advanced piston corer (APC) system to take Cores U1579A-1H through 8H, with the last material recovered at 74.78 m core depth below seafloor (CSF-A). The advanced piston corer temperature (APCT-3) tool was run on Cores 4H and 7H. After firing Core 9H from 74.6 m CSF-A, the core barrel became stuck. The core barrel was retrieved; however, all that was recovered was a sheared overshot and the sinker bars, and the decision was made to abandon the hole. A total of 9 cores were taken in Hole U1579A over an 84.1 m interval with 87% recovery. Total time on Hole U1579A was 33.12 h (1.38 d).

Hole U1579B was spudded at 0910 h on 14 February. We used the APC system to take Cores U1579B-1H to 6H (to 57.0 m CSF-A), and switched to half-length APC (HLAPC) coring for Cores 7F–24F (to 141.6 m CSF-A). The extended core barrel (XCB) system was used to take the final cores (25X to 27X). A total of 27 cores were taken in Hole U1579B over a 167.08 m interval with 99% recovery. The rate of penetration for XCB cores (3) averaged 11 m/h. Total time on Hole U1579B was 40.56 h (1.69 d).

Hole U1579C was spudded at 1720 h on 15 February. The hole was drilled down with a center bit by 56.5 m. We used the HLAPC system to take Cores U1579C-2F to 21F (to 130.5 m CSF-A), with five small (0.5 to 1.5 m) advances without recovery for stratigraphic correlation. We then drilled down an additional 31.5 m and used the XCB system to take Cores 23X to 25X, although Core 23X did not recover any material. Heave was making it difficult to keep the bit on bottom and the decision was made to terminate coring at the final depth of 186.9 m CSF-A. A total of 18 cores were taken in Hole U1579C over a 93.4 m interval with 80% recovery. The rate of penetration for XCB cores (3) averaged 9.6 m/h. Total time on Hole U1579C was 42.24 h (1.76 d).

Hole U1579D was spudded at 2124 h on 17 February and drilled down to 130 m CSF-A. We used the rotary core barrel (RCB) system to take Cores U1579D-2R through 65R (to 727.2 m CSF-A). On 24 February the bit was released in the bottom of the hole at 0310 h and the hole was displaced with heavy mud in preparation for logging. The 48 m long "quad combo" tool consisted of the Hostile Environment Litho-Density Sonde (HLDS), Dipole Shear Sonic Imager (DSI), High Resolution Laterolog Array (HRLA), Hostile Environment Natural Gamma Ray Sonde (HNGS), and Magnetic Susceptibility Sonde (MSS). The downlog was paused to conduct a high resolution uplog from 450 to 250 m CSF-A. After resuming the downlog, the tool tagged 727.7 m CSF-A, and an uplog was done. Pipe was tripped back to the rig floor and Hole U1579D ended at 0735 h. A total of 64 cores were taken in Hole U1579D over a 597.2 m interval with 73.8% recovery. The rate of penetration for RCB coring averaged just under 20 m/h in the sediment to 2.0 m/h in basalt, with an average rate of 8.2 m/h. Total time on Hole U1579D was 188.4 h (7.85 d).

Principal Results

Lithostratigraphy

A ~634 m thick sequence of calcareous sediments of Pleistocene–Santonian age overlying zeolitic siliciclastic sediments and basalt was recovered at Site U1579. The main sedimentary succession down to ~697 m is divided into Lithostratigraphic Units I–III, with Unit II further subdivided into Subunits IIa–IIc. Below Unit III, a ~24 m thick interval of basalt is designated as Unit IV, which overlies another ~5 m of zeolitic siliciclastic sediments (Unit V) and ~2 m of basalt (Unit VI).

Lithostratigraphic Unit I (Hole U1579A: 0–1.31 m CSF-A; Hole U1579B: 0–6.19 m CSF-A) consists of light gray nannofossil-rich foraminiferal ooze, with average carbonate concentrations of ~90 wt% $CaCO_3$. Unit I is differentiated from the underlying white nannofossil ooze of Unit II on the basis of a greater abundance of foraminifers and a darker light gray color. The light gray color reflects a greater abundance of sand-sized glauconite grains, disseminated pyrite, and clay. Unit II consists of ~630 m of Miocene–Campanian carbonate ooze and chalk (top: 1.31 m CSF-A in Hole U1579A, 6.19 m CSF-A in Hole U1579B; base: 634.72 m CSF-A in Hole U1579D). The primary sedimentary components of Unit II are calcareous nannofossils and recrystallized calcite, with varying abundance of foraminifers and clay. Unit II is subdivided into Subunits IIa–IIc on the basis of lithification (ooze vs. chalk), color, and the occurrence of thin silicified horizons. Unit III (634.72–697.00 m CSF-A, Hole U1579D) consists of ~60 m of greenish-gray well-lithified zeolitic siliciclastic sediments (sandstones, siltstones, and claystones) with glauconite. Most individual clasts are likely of volcaniclastic origin which have undergone significant alteration to clay minerals and zeolites, with carbonate cementation. Rare carbonate bioclasts and foraminifers suggest marine deposition. The variety of processes influencing the composition of Unit III (volcanism, siliciclastic sedimentation, and alteration) suggests a complex history of sedimentation and post-depositional diagenesis.

Lithostratigraphic Unit V (720.90–725.47 m CSF-A, Hole U1579D) consists of a ~5 m thick interval of greenish-gray sediments that were recovered between basalt Units IV and VI (see below). Unit V is of a similar lithological character to Unit III but is physically separated from Unit III by basalt Unit IV. As described for Unit III, Unit V consists of well-lithified greenish-gray zeolitic siltstone and sandstone sediments with glauconite. The lower contact of the sediments of Unit V with the underlying basalt of Unit VI at ~725 m CSF-A provides important clues to the emplacement of the basalt. Across the ~50 cm immediately above the contact, sediment color gradually lightens downcore from greenish-gray to light greenish-gray, while individual grains and sedimentary structures become less distinct. This change in sedimentary character is interpreted as evidence for contact metamorphism in the sediment due to heating following intrusion of Unit VI.

Igneous Petrology

Igneous rocks were reached at 697.0 m CSF-A in Hole U1579D below sedimentary Lithostratigraphic Unit III. A 23.8 m thick massive interval (Unit IV) was cored between 697.0 and 720.8 m CSF-A, below which a 4.57 m thick sedimentary sequence (Unit V) was encountered (720.8–725.3 m CSF-A). This sequence was underlain by another massive igneous unit (Unit VI; 725.3–727.2 m CSF-A), of which 1.8 m was cored before drilling in Hole U1579D was terminated at a final depth of 727.2 m CSF-A. Lithostratigraphic Unit IV (Igneous Unit 1; 697.00–720.77 m CSF-A) is composed of plagioclase-clinopyroxene phyric basalt. The unit grades downsection toward less vesicular and more coarse-grained textures, and the central portion of the unit is well-crystalized and medium-grained. From the central part of the unit downsection, the groundmass grain size decreases to fine grained and eventually aphanitic at its lower contact. No abrupt or significant lithological changes (e.g., different mineralogy or multiple cooling units) could be recognized within the 23.8 m thick igneous succession of Unit IV (Igneous Unit 1). Lithostratigraphic Unit VI (Igneous Unit 2; 725.47–727.285 m CSF-A) is composed of nearly aphyric basalt and is moderately vesicular (with all vesicles being filled with alteration minerals) and shows a fine-grained groundmass.

Basalt Units IV and VI recovered in Hole U1579D are interpreted to be sills based on systematic lithological variations towards their upper and lower margins and the characteristics of the sediments at the contact zones. Both units show relatively wide (>20 cm) chilled (and altered) zones but without significant brecciation. Unit IV, which was completely penetrated, also shows a spatial increase in groundmass grain size towards its center. Accordingly, both units show more characteristics of sills than lava flows. More importantly, the sediments at the contact zones above both the upper and lower igneous bodies show alteration reactions such as brick-red colored streaks characteristic of thermal “baking,” including also bleaching and recrystallization.

Micropaleontology

The sedimentary succession recovered at Site U1579 contains calcareous nannofossils, foraminifers, siliceous microfossils, and palynomorphs in varying abundance and preservation. Calcareous nannofossils are generally abundant and moderately to well preserved above 635 m CSF-A (Lithostratigraphic Units I and II) and provide the primary means of biostratigraphic age control for the calcareous sediments (Units I and II) recovered at Site U1579. Planktonic foraminifers are also generally abundant and moderately to well preserved above 635 m CSF-A and also provide supporting age control for the calcareous sediments. Benthic foraminifers, however, are present in significantly fewer numbers. Radiolarians, together with sparse silicoflagellates and diatoms, are present only across the Eocene–Oligocene transition (EOT) interval. Palynomorphs, including dinoflagellate cysts (dinocysts), pollen, and spores, are found in discrete organic-rich layers below 635 m CSF-A and provide important age control in the lower part of the sedimentary succession (Lithostratigraphic Unit III), which is nearly devoid of carbonate and siliceous microfossils.

Chronostratigraphy

Calcareous nannofossils, planktonic and benthic foraminifers, dinocysts, and magnetostratigraphy provide age control for the Santonian–lower Miocene sediments recovered at Site U1579. Very few age constraints were identified in shipboard work for the lowermost part of the sedimentary sequence recovered at Site U1579 (below ~600 m CSF-A). However, an early Santonian age (86.8–85.2 Ma) is indicated by the dinocyst assemblage at 673.75 m CSF-A, which is consistent with the interpretation of the persistent normal polarity in this interval to represent magnetochron C34n (the Cretaceous Normal Superchron). Calcareous nannofossil, planktonic foraminiferal, and benthic foraminiferal biostratigraphy and magnetostratigraphy further constrain the age of the sedimentary sequence between ~608 and 505 m CSF-A to the Late Cretaceous Campanian and Maastrichtian stages (83.7 to 66.0 Ma). The K/Pg boundary was recovered in Core U1579D-33R, with the base of the Paleocene identified at a thin greenish-gray clay at 433.26 m CSF-A. This placement was confirmed by benthic foraminiferal biostratigraphy, in addition to the top of Cretaceous calcareous nannoflora at 433.29 m CSF-A, which demarcates the end of the Cretaceous. The identification of the top of magnetochron C30n at 438.46 m CSF-A supports this interpretation.

Calcareous nannofossil biostratigraphy provides the primary means of age control for Paleocene–lower Miocene sediments recovered in the upper part of Site U1579, with support from planktonic foraminiferal biostratigraphy and magnetostratigraphy. The basal Eocene (~56.0 Ma) was identified in Core 392-U1579D-16R (267.14 m CSF-A). Between the K/Pg boundary and basal Eocene, 14 nannofossil biohorizons and six paleomagnetic reversals provide good age control for the Paleocene sediments. The Eocene/Oligocene boundary (33.9 Ma) is identified between 175.74 and 167.97 m CSF-A. Between the basal Eocene and

Eocene/Oligocene boundary, 18 nannofossil biohorizons and two paleomagnetic reversals provide good age control for the Eocene section of Site U1579.

Near the top of the recovered sedimentary section at Site U1579, a disconformity separates a thin veneer (~1–6 m thick) of Pleistocene sediments from the underlying sediments, which are dated approximately to the Oligocene/Miocene boundary (23.04 Ma) based on calcareous nannofossil biostratigraphy. Thirteen calcareous nannofossil and three foraminifer datums provide good age control for the Oligocene sediments recovered at Site U1579 (~168 to 1–6 m CSF-A).

Paleomagnetism

Paleomagnetic measurements were performed on all archive section halves from Site U1579, in addition to 131 discrete samples. The primary purpose of these measurements was to determine magnetic polarity stratigraphy. However, additional rock magnetic experiments (anisotropy of magnetic susceptibility (AMS) and isothermal remanent magnetization (IRM) acquisition) were performed to further inform on the reliability of magnetic signals, magnetic fabric, and environmental/postdepositional processes.

Within Lithostratigraphic Unit I and Subunit IIa (foraminiferal and nannofossil oozes; 0 to ~145 m CSF-A), a reliable magnetostratigraphy was not determined due to the low magnetization intensities of the samples. In Lithostratigraphic Subunits IIb and IIc (nannofossil and calcareous chalks; ~145 to 635 m CSF-A) and Unit III (zeolitic siltstones and sandstones; ~635 to 697 m CSF-A), the determination of a complete magnetostratigraphy is also not possible, again due to the low magnetization of the samples. However, using biostratigraphic constraints, in some regions of both Lithostratigraphic Subunit IIb and Unit III, it is possible to determine distinct polarities and correlate these to chrons within the geomagnetic polarity timescale (GPTS) from the Geologic Time Scale 2020 (GTS2020) (Gradstein et al., 2020; Ogg, 2020). These include chrons C24n.3n (255.16–261.63 m CSF-A), C27n (382.165–389.075 m CSF-A), C27r (389.075–404.015 m CSF-A), C28n (404.015–420.485 m CSF-A), C28r (420.485–424.07 m CSF-A), C29n (424.07–432.4075 m CSF-A), C29r (432.408–438.462 m CSF-A), C33r (583.105–607.858 m CSF-A), and C34n (607.585 m CSF-A and continued beyond the base of Hole U1579D). All of the zeolitic siltstone to sandstone with glauconite and the basalt units have normal polarity that are assigned to chron C34n.

Stratigraphic Correlation

The physical property records of Holes U1579A, U1579B, U1579C, and U1579D were compared, and correlated where possible, to establish a common depth scale. Tie points were identified using natural gamma ray (NGR), magnetic susceptibility (MS) from the Whole-Round Multisensor Logger (WRMSL), color reflectance data, high-resolution digital core images, and red-green-blue color space (RGB) data extracted from the digital core images. A composite record was spliced for the upper 147 m core composite depth below seafloor (CCSF) of the recovered stratigraphic succession. Small recovery gaps in the composite record exist at 66.00 to

66.57 m CCSF and 93.54 to 93.68 m CCSF. From 147 to 163.87 m CCSF, a complete composite record could not be established due to no overlapping cores from parallel holes. From 163.87 to 182.07 m CCSF, a composite record was made stitching cores together from Holes U1579B and U1579D. Below 182.07 m CCSF, cores from Hole U1579D do not have parallel drilled sections.

Recognition of matching patterns in NGR records from cores and wireline logging in Hole U1579D permitted translation of core depth scales from CSF-A to wireline log matched depth below seafloor (WMSF). The correlation between NGR signals in the retrieved sediment core and downhole logging datasets is excellent, allowing the segments of recovered core intervals to be tightly correlated to the continuous borehole logging data.

Geochemistry

The geochemistry program at Site U1579 was designed to characterize the composition of bulk sediment and interstitial water (IW) and report on the presence and abundance of volatile hydrocarbons for routine safety monitoring. In total, 73 headspace samples were analyzed for routine safety monitoring. Methane concentrations are overall very low throughout Site U1579, generally ranging between 0 and 12 ppmv, with the highest methane concentration of 21 ppmv observed at 386.92 m CSF-A. Higher hydrocarbons are not detected, except at 420.94 m CSF-A, where traces of isopentane (0.14 ppmv) are present.

IW samples were analyzed in Holes U1579A–U1579D down to 497.08 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. From the top of section to 496.98 m CSF-A, alkalinity values increase from 2.9 to 15.4 mM, and pH values decrease from ~7.7 to ~7.0. Sulfate decreases from ~29 mM immediately below the seafloor to ~22 mM at ~280 m CSF-A, and then remains relatively constant downhole to ~497 m CSF-A. Chloride and sodium both increase downhole over their seawater values (557 mM and 481 mM) to roughly 610 mM and 510 mM, respectively, at ~497 m CSF-A. Calcium increases downhole from 10.77 mM immediately below the seafloor to 27.54 mM at ~497 m CSF-A, and magnesium decreases downhole from 51.68 mM to 46.14 mM at 253 m CSF-A, before increasing to a value of ~49 mM at the base of the record.

Sediment samples were analyzed for carbon and nitrogen concentration in Holes U1579A–U1579D down to 695.68 m CSF-A. In the upper ~450 m of the sedimentary sequences, carbonate concentration is high (~60%–95%), which is consistent with the deposition of largely pelagic nannofossil ooze and chalks. Significant variability in carbonate content is observed between ~150 to 300 m CSF-A, and generally lower carbonate concentrations are determined below ~450 m CSF-A. Below ~630 m CSF-A (Lithostratigraphic Unit III), carbonate content decreases to an average of ~24%; the carbonate in this lower interval may include other carbonate minerals such as siderite and dolomite. The average total organic carbon content of Site U1579 sediment samples is 0.324% ± 0.19%, with minimum and maximum concentrations of 0% and 0.99%, respectively. The low organic carbon content reflects the calcareous ooze and chalk character of Lithostratigraphic Units I and II.

Physical Properties

Physical properties of sediments and igneous rocks recovered at Site U1579 were measured on whole-round core sections, split half core sections, and discrete samples from each hole at the site to a total depth of 727.3 m CSF-A. In the upper 182 m of the site, the holes overlap stratigraphically and physical property data were used to construct a near-complete composite splice.

NGR and MS varied among the lithological units. Lithostratigraphic Unit I is characterized by relatively high NGR and low MS values, while Subunit IIa (~4 to 147.10 m CSF-A) has lower average values for both parameters. Greater variability is observed in Subunits IIb and IIc (149.40 to 634.72 m CSF-A). In the basalts of Lithostratigraphic Units IV (from 697.00 to 720.77 m CSF-A) and VI (from 725.47 to 727.29 m CSF-A), NGR values are lower while MS shows the highest values.

Moisture and density (MAD) analyses were performed on 139 discrete samples. Bulk density increases downcore following a general trend of porosity reduction. The density values are higher in Lithostratigraphic Subunit IIc but low in Lithostratigraphic Unit III. Contact *P*-wave velocities data were measured with the *P*-wave caliper system (PWC) from working-half core sections (1–2 per core, 163 measurements in total) and from 3 discrete cubic samples (9 measurements). In Lithostratigraphic Unit I and Subunit IIa (0 to 147.10 m CSF-A), *P*-wave velocities vary in a narrow range of 1560–1600 m/s. Higher *P*-wave velocities of ~2000–2150 m/s characterize the nannofossil chalk of Lithostratigraphic Subunit IIb down to a depth of ~500 m CSF-A. In the chert-rich nannofossil chalk of Lithostratigraphic Subunit IIc, the velocity significantly increases to 2500–3500 km/s between 556 and 635 m CSF-A. Average *P*-wave velocities in the underlying altered zeolitic siltstones and sandstones (Lithostratigraphic Units III and V) and basalts (Lithostratigraphic Units IV and VI) are 2500–3000 km/s and 4500–5600 km/s, respectively.

Thermal conductivity measured on soft sediment whole-round sections show a general increase downhole. Values are higher in the basalts of Lithostratigraphic Unit IV (~700–720 m CSF-A), with lower values in this range reflecting more vesicular structures and interbedded sediments.

Downhole Measurements

Hole U1579D was logged using the “quad combo” tool string, which consisted of the Lamont-Doherty Earth Observatory MSS, the HNGS, the HRLA, DSI, and the HLDS. A high resolution run between 450 and 250 m WMSF covering the condensed Eocene–Oligocene interval was followed by a normal resolution pass over the full depth of Hole U1579D. NGR values again show variation with lithology with largest values in the zeolitic silicified silt- and sandstones.

The basalts of Unit IV (below 697 m WMSF) show the lowest values. Increased resistivity corresponds to zones of chalk beds with claystone and chert of Unit IIc (see Lithostratigraphy). The highest resistivity values (100–300 Ω·m) were recorded in basalts of Unit IV. The downhole wireline density generally follows the *P*-wave velocity trend. A distinct offset between the *P*-wave velocities measured at the core and downhole can be observed. Within Lithostratigraphic Unit IIb (200–556 m WMSF) the DSI *P*-wave velocity is 2000–2500 m/s, which is about 300 m/s higher than measured in the laboratory.

References

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