IODP Expedition 391: Walvis Ridge Hotspot

Site U1578 Summary

Background and Objectives

Site U1578 (proposed Site CT-05A) is the westernmost drilling location for Expedition 391, and it is the youngest, with an expected age either in the latest Cretaceous or earliest Paleocene. It is the only Expedition 391 site in the morphologically distinct Guyot Province. With >300 m of igneous basement cored, it is also the deepest basement penetration site of Expedition 391. The site, situated on the Center Track ridge between the Tristan and Gough hotspot tracks, was chosen because the erupted lavas are either likely to be a mixture of Tristan- and Gough-type components or constitute a distinct third isotopic signature. A major objective for this site is to measure the geochemical composition of samples from a deep downhole section of lava flows. The geochemistry should offer clues to the magma source and evolution of the Center Track ridge. Although there are already many radiometric dates for Walvis Ridge seamounts, samples from Site U1578 help fill gaps in prior sampling, strengthening the age progression. The expected age for Site U1578 basement is a propitious time for understanding the paleolatitude changes of the Tristan-Gough-Walvis (TGW) hotspot, because global paleomagnetic data sets suggest that the paleolatitude for the latest Cretaceous and earliest Paleocene TGW hotspot location was south of its current latitude, implying northward motion. In contrast, hotspot drift models imply the opposite sense of motion. Moreover, the sense of motion may be opposite to the Hawaiian hotspot, which would confirm true polar wander. Although the location of Site U1578 was selected to minimize sediment cover, the sedimentary sequence is expected to provide insights into paleoceanographic conditions at Walvis Ridge during the Cenozoic.

Operations

A single hole was drilled at Site U1578. Hole U1578A is located at 32°19.6836′S, 0°38.5876′W in a water depth of 3793.8 m as obtained from the driller's tag depth. In Hole U1578A, we used the rotary core barrel (RCB) coring system to advance from the seafloor to a final depth of 486.4 m below seafloor (mbsf) and recovered 239.9 m (49%) of sediment and igneous rock. The total advance in Hole U1578A required the deployment of two RCB coring bits through a bit change and reentry of the hole. In total, Hole U1578A penetrated 302.1 m of igneous basement. The total time spent on Hole U1578A was 244.0 h, or 10.2 days.

Principal Results

Sedimentology

An ~184 m thick succession of calcareous pelagic sediment interbedded with volcaniclastic layers lies on top of a volcanic basement. Two main lithostratigraphic units, with the second further divided into two subunits, were recognized based on macroscopic and microscopic (smear slide, thin section, and scanning electron microscopy) lithological observations along with changes in magnetic susceptibility (MS), natural gamma radiation (NGR), and biostratigraphic data. These overlie the igneous succession which consists of lava stacks intercalated with 10 sediment interbeds.

Unit I forms the uppermost 27 m of the sedimentary cover. It consists of Pleistocene to Pliocene white to pale brown foraminifera-nannofossil ooze with clay. Significant drilling disturbance occurs throughout due to poor consolidation of this pelagic sediment, but almost complete (99%) recovery was achieved. A mass transport deposit occurs toward the boundary with underlying Unit II in Section U1578A-3R-6. The boundary itself is marked by the appearance of tephra and a gradual clay increase in the calcareous ooze/chalk downhole, which correlate with an increase in MS and NGR values, as well as the occurrence of Eocene/Paleocene foraminifera and nannofossil assemblages indicating a significant stratigraphic gap.

Unit II is an ~157 m thick succession of mostly Paleocene calcareous pelagic sediment with rare volcaniclastic deposits that becomes progressively more consolidated with depth. Relatively limited (<40%) recovery in this unit probably occurred due to significant heave motion during drilling. Two subunits (Subunits IIA and IIB) were defined in Unit II based on changes in clay content and NGR values. Subunit IIA is early Eocene to Paleocene in age and occurs from 27.00 to 135.20 mbsf. It consists of white to pale pinkish-brown nannofossil ooze to chalk with clay and rare radiolarians, siliceous sponge spicules, and small foraminifera. The unit also includes minor (commonly disturbed) interbeds of light to dark gray tephra with colorless to light brown highly vesicular volcanic glass and pumices. Subunit IIB is Paleocene in age and occurs from 135.20 to 184.26 mbsf, down to the top of the underlying volcanic succession. It consists of light gray to greenish-gray clayey-nannofossil chalk with rare radiolarians, siliceous sponge spicules, and small foraminifera. The chalk lithology is darker and more clayey than that of Subunit IIA, consistent with a gradual increase in NGR in the lower part of the sedimentary cover. Subunit IIB also includes minor interbeds of dark greenish-gray to black vitric sandstone/tuff with normal grading that increase in abundance toward the top of the volcanic basement. Volcanic glass shards in the dark sandstone/tuff are fresh to altered with highly vesicular to pumiceous textures, but they are distinctively browner than glass shards of overlying Subunit IIA. The texture of the tephra and sedimentary structures of volcaniclastic beds suggest shallow marine, and possibly subaerial, volcanism with synvolcanic deposition during pelagic fallout, and/or syn- to postvolcanic reworking by turbidity and/or bottom currents.

This sedimentary succession overlies igneous basement, which consists of 12 igneous lithologic units. These units consist of massive flows alternating with thick pillow lava stacks, with rare peperitic intervals and 10 sedimentary interbeds. These interbeds vary in thickness between ~>0.5 and >10 m and occur to a depth of 416.87 mbsf. They are lithologically similar to the lowermost sedimentary cover and are composed of clayey-nannofossil chalk with volcaniclastic layers. The volcaniclastic deposits typically consist of turbidites with variably altered vitric clasts. The glass shards are very vesicular in the topmost six sedimentary intervals and become poorly vesicular in the lower part of the hole.

Igneous Petrology and Volcanology

Hole U1578A penetrated 302.12 m of igneous basement (interval U1578A-20R-1, 46 cm, through 65R-3, 45 cm) with 181.26 m (59.9%) recovery. The igneous basement at Site U1578 represents Lithostratigraphic Unit III in the overall subseafloor succession. Hole U1578A terminates in a pillow lava unit with a minimum thickness of 67 m. Twelve igneous units were identified in Hole U1578A. The units comprise pillow and lobate lava flows, sheet flows, and massive flows with interbedded sediments. The changing eruptive style, changes in chemistry, and the pelagic sediment interbeds suggest episodic volcanic activity. The uppermost 96 m of the succession consist largely of sheet and massive flows intercalated with volcanic sands and silts; pillow lava flows are present in thin sequences. The dominant unit below that comprises 96 m of continuous pillow basalt, followed by 109 m of pillow lava with two massive flows and one 6.3 m thick sediment horizon. Glass rims were preserved on many pillow margins. The massive flows can be quite voluminous, with one massive basalt unit at least 14.9 m thick. The lavas range from highly phyric (~8%–15% plagioclase, 0%–4% olivine, and 1%–3% pyroxene) to sparsely phyric or aphyric basalts. In highly phyric lavas, plagioclase phenocrysts and glomerocrysts can be up to 15 mm in diameter; pyroxene and olivine are generally much smaller (1–3 mm). Thicker massive units present relatively fresh rock, while pillow units are pervasively altered; the exception is very fine-grained pillows that preserve primary modal compositions in their interior. The vesicular and fractured nature of pillow lava stacks makes them susceptible to mineralization in the form of vesicle infilling and veins in fractures. The nature of this alteration changes downward through the succession with carbonate and calcite, together with Fe-oxyhydroxide dominating the upper igneous lithologic units, and pyrite (marcasite) together with Cu-bearing coatings and zeolites infillings becoming more common downhole. Further within the volcanic sequence there is distinctive epidote mineralization along fractures and within pillow lava vesicles.

Biostratigraphy

Preliminary calcareous nannofossil and planktonic foraminifera biostratigraphy was conducted on core catcher (CC) sections from Hole U1578A. A preliminary chronostratigraphic framework for sediments in this hole was obtained from the stratigraphic distribution of the investigated microfossil groups, referring to biozonations that are based on Gradstein et al. (2012, 2020). Calcareous nannofossil analysis was conducted on 18 CC sections and on 10 toothpick samples

taken from within core sections. Planktonic foraminifera were analyzed in a total of 10 CC samples to provide additional key age controls. Foraminifera sample preparation required the use of hydrogen peroxide (30%) to disaggregate lithified sediments, which limited the time available for shipboard analysis. Overall, calcareous nannofossils and planktonic foraminifera are in good agreement at Site U1578.

Calcareous nannofossils show good preservation and high abundances throughout Hole U1578A. Planktonic foraminifera are well-preserved and abundant in the upper part of the stratigraphic sequence (Sections U1578A-1R-CC and 2R-CC; Unit I). Conversely, foraminifera abundances decrease downhole (Sections 3R-CC to 18R-CC), where an increase in radiolarians was noted. Moreover, planktonic foraminifera show a decrease in test size in the same time interval, which possibly indicates a response to environmental stress. Sections 1R-CC and 2R-CC record late Pliocene (Piacenzian) to Pleistocene (<0.43 Ma) sediments. Toothpick samples for calcareous nannofossil analysis were taken from Section 2R-5 to investigate a lithological change that was thought to be an additional age horizon. The examined samples revealed the presence of Oligocene and mixed Eocene flora, separating Gelasian (early Pleistocene) sediments. The occurrence of older taxa within the Pleistocene deposits may be indicative of sediment remobilization (e.g., slump/landslide). The existence of a major unconformity between early Pliocene (Zanclean) and Paleogene deposits at ~27.0 mbsf was confirmed by both calcareous nannofossil and planktonic foraminifera data. A shift in MS and magnetic remanence values were also observed from the same depth interval, supporting the presence of the unconformity. Sections 3R-CC to 18R-CC recovered a continuous Paleogene stratigraphic sequence. Uncertainties in the placement of the Eocene/Paleocene boundary derived from the analysis of calcareous nannofossil and planktonic foraminifera assemblages. Planktonic foraminifera data indicate a mix of early Eocene (Ypresian) and late Paleocene (Thanetian) taxa in Section 3R-CC. Calcareous nannofossils suggest a possible early Eocene age for the same sample, as the late Paleocene marker *Ericsonia robusta* (56.78 Ma) is not observed until Section 5R-CC. The bottommost section 18R-CC, at the sediment-basement contact, is dated between 61.98 and 62.07 Ma based on calcareous nannofossils. Planktonic foraminifera suggest a possibly older age (62.2–63.5 Ma), but this date is considered unreliable due to the scarce abundance of foraminifera specimens in the section.

Interbedded sediments within the basement section were investigated using calcareous nannofossils. Preliminary shipboard analyses indicate a possible age of ~63.25–64.81 Ma. However, high-resolution postexpedition examination is required to better evaluate the age of the intercalated sediments. Preliminary biostratigraphic data from the chalk units of the uppermost five interbeds indicate a Paleocene (Danian) age of deposition.

Paleomagnetism

Sediment Cores U1578A-1R through 19R are made of ooze to chalk with varying clay content. Core archive halves and discrete samples were analyzed using the superconducting rock magnetometer and JR-6A spinner magnetometer, respectively. Sediment natural remanent

magnetization (NRM) values range from 10^{-4} to 10^{-1} A/m. Most sediments have median destructive fields ranging from 30 to 50 mT. Thermal demagnetization spectra of sediment specimens often revealed slow unblocking of magnetization starting from 200°C and sometimes persisting to 600°C. This demagnetization behavior suggests that the dominant magnetization carriers in sediments from Hole U1578A are likely a mixture of titanomagnetite with varying Ti concentrations, magnetite, and hematite. We did not assign polarity chrons (C) to Cores 1R through 3R, because there was high dispersion in magnetic inclination values for those cores. However, we were able to assemble a magnetostratigraphy spanning six polarity chrons starting with C24r in Core 4R through the top of C27n in Core 19R that was located just above the contact with basement.

Igneous rocks recovered from Site U1578 span Cores 19R through 65R and primarily consist of basalt. Occasionally, layers of sedimentary rocks or hyaloclastites were observed between basalt flows. The igneous rocks typically have NRM values ranging from 10^{0} to 10^{1} A/m. After alternating field (AF) cleaning to 20 mT, igneous rocks from Cores 20R through 45R dominantly display a negative inclination magnetization consistent with them having formed during a normal polarity interval. A brief reverse polarity chron in Core 23R could possibly represent C27r (63.5–62.5 Ma), but it could also be attributable to secondary chemical remagnetization or unsuccessful removal of drill string overprints during partial AF demagnetization. Demagnetization of discrete samples from Cores 38R to 44R had an unusually high failure rate. Cores 46R through 65R dominantly display a positive inclination magnetization consistent with formation during a reversed polarity interval. This suggests that at least one geomagnetic reversal is recorded in the eruptive sequence at Site U1578. Most of the igneous rocks have median destructive field values between 5 and 25 mT and exhibit a range of thermal demagnetization behaviors, with maximum unblocking temperatures ranging between ~200° and 580°C, the latter being the Curie temperature of magnetite. This wide range of thermal demagnetization behaviors implies the coexistence of several magnetic phases such as magnetite and titanomagnetite with a large range of Ti content.

Geochemistry

At Site U1578, interstitial water (IW) samples were analyzed for pH, alkalinity, and concentrations of major cations, anions, and trace elements. Both alkalinity and pH show narrow ranges. IW calcium concentration increases downhole to 30 mbsf and slowly decreases below this depth, while IW magnesium concentration shows a decreasing trend throughout the sediment succession. IW silicon concentration increases from ~200 μM at the top of the sediment to ~700 μM at ~50 mbsf and maintains the high concentration of 600–800 μM throughout the lower sediment succession. IW lithium concentration decreases downhole to 50 mbsf and remains at the low concentration of ~21 μM below this depth, showing a trend generally opposite to IW silicon. IW manganese concentration shows a narrow peak near the top of the sediment and a broad peak close to the bottom of the sediment succession. Summarizing, IW geochemistry at Site U1578 is affected by diagenesis of biogenic carbonates at shallow depths and diageneses of biogenic silica at deep depths. Sediment samples were also analyzed for the contents of $CaCO_3$,

total carbon, and total organic carbon. $CaCO_3$ content declines in Unit II, while organic carbon content is consistently low in the sediments. Methane concentrations measured from the headspace gas are lower than the atmospheric background level of 2.0 µL/L.

Site U1578 recovered 12 igneous units of aphyric and highly phyric massive basalt flows. For the determinations of major and trace elements, 16 samples from the first eight units were analyzed by inductively coupled plasma–atomic emission spectroscopy. Additionally, 343 measurements were conducted on archive half section pieces along the entire hole by portable X-ray fluorescence. The loss on ignition (LOI) represents an indicator for the degree of alteration and the analyzed samples show LOI with <3 wt%, which is relatively fresh given that they represent presumably old submarine rocks. An overall increase in the scatter of K_2O data might be due to limited mobility for potassium during seawater alteration, but there are no other indications for element variability due to alteration. All samples from Site U1578 are classified as basalts, except one hawaiite sample, and have an alkalic composition. In contrast to the previously drilled Expedition 391 sites, the Ti-V composition of the basalts from Site U1578 are comparable to the Ocean Island Basalt array and similar to other alkaline intraplate lavas previously reported from the Tristan-Gough hotspot track. Based on the TiO_2 content, the samples are subdivided into: high-Ti with TiO_2 <3.4 wt% and very high-Ti rocks with TiO_2 ≥ 3.9 wt%. In bivariate diagrams, the major and trace element trends of the high-Ti rocks are in general consistent with olivine, Cr-spinel, and pyroxene fractionation. The very high-Ti rocks are offset relative to the high-Ti rocks to overall higher TiO_2, Fe_2O_3, MnO, Sc, V, Co, Zn, and Y values, but lower SiO_2, Al_2O_3, and K_2O contents for a given Mg#. Site U1578 represents the longest basement interval drilled during IODP Expedition 391 and significant downhole geochemical variations are observed. The TiO_2 content, for example, is relatively low with 2.5–3.3 wt% in the upper part of the recovered core. In Unit 8 the rocks are characterized by very high TiO_2 values with 4.0–4.5 wt%, which steps down to values averaging 3.6 wt% in Unit 9 and then gradually decreases downhole to Units 11 and 12, where TiO_2 is comparable to the upper part of the basement succession.

Physical Properties

Three general lithostratigraphic intervals were identified in Hole U1578A based upon physical properties measurements, including NGR, MS/point magnetic susceptibility (MSP), bulk density, thermal conductivity, *P*-wave velocity, and porosity. The first interval, calcareous ooze and chalk, may be further subdivided into an upper and a lower unit based upon NGR, gamma ray attenuation (GRA) and moisture and density (MAD) bulk density, and MS/MSP values. At ~30 mbsf, a pronounced increase in MS/MSP (up to 79.3×10^{-5} SI from a background of ~2.68 to ~7.23×10^{-5} SI) and NGR (up to ~19.5 counts/s from a background range of ~2.25 to ~4.14 counts/s) and a decrease in GRA/MAD bulk density (from ~1.87 to ~1.74 g/cm^2 across the unit contact) define the boundary between lithostratigraphic Units I and IIA. Below the ~184 mbsf calcareous sediment-basalt contact, basalt units and volcaniclastic interbeds are distinguished by porosity (~34.1 and ~58.3 vol% in volcaniclastic interbeds vs. ~6.29 and ~15.6 vol% in basalts) and thermal conductivity (1.05 to 1.33 W/[m·K] in volcanic clastic

interbeds vs. 1.66 to 1.77 W/[m·K] in basalts). Increases in MS/MSP, *P*-wave velocity, and GRA/MAD bulk density also accompany the shift from volcaniclastic interbeds to basalt units. Physical properties measurements also appear to image mineralogical and compositional trends within basalt units. Olivine-phyric flows correlate to higher (>3000 × 10^{-5} SI) MS/MSP at ~218 and ~253 mbsf, and an anomalously high NGR count at ~270 mbsf appears to correlate to a high potassium aphyric basalt at the same depth.

References

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), 2012. The Geologic Time Scale 2012, Elsevier, vol. 1, 437–1127. ISBN: 978-0-44-459448-8.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), 2020. The Geologic Time Scale 2020, Elsevier, vol. 2, 565–1357, ISBN: 978-0-12-824363-3.