IODP Expedition 391: Walvis Ridge Hotspot

Site U1575 Summary

Background and Objectives

Site U1575 (proposed Site FR-01B) is located within a low saddle on the northeastern end of the Walvis Ridge between the higher Frio Ridge (near the continental margin) and Valdivia Bank, a large ocean plateau edifice. This site was chosen as the eastern (older) end of the Expedition 391 transect because it represented an opportunity to sample a part of the ridge that cannot be sampled by dredging due to sediment cover. It also represents the hotspot trail shortly after it passed from the African continental margin to oceanic crust. Trace element and isotopic geochemistry can provide insights into the transition from the plume head to plume tail stage of hotspots, specifically whether both high-TiO_2 (Gough-type) and low-TiO_2 (Doros-type) basalts are present in the plume tail, as have been found in the Etendeka (and Parana) flood basalts (plume head stage). Furthermore, does the Tristan signature, which is found in the younger chain (seamount chain going from Walvis Ridge DSDP Site 527 to Tristan da Cunha Island), appear in the older portion of the ridge, extending the geochemical zonation of the hotspot track further back in time? The drill cores provided samples that can show the eruption age of the main Tristan-Gough-Walvis hotspot track, in an area that is often overprinted with late-stage volcanism. Furthermore, Site U1575 provided paleomagnetic samples for a time when the hotspot is predicted to have been ~5° north of its current paleolatitude, but a time when the paleolatitude was rapidly changing. The site also contained sediments deposited near the Benguela current, in a regime that is transitional from continental margin siliciclastic to open-ocean pelagic carbonate deposition, which can reveal past marine environmental conditions.

Operations

A single hole was cored at Site U1575. Hole U1575A is located at 21°51.9659′S, 6°35.4369′E in a water depth of 3231.3 m as obtained from the precision depth recorder. In Hole U1575A, we used the rotary core barrel coring system to advance from the seafloor to a final depth of 332.3 m below seafloor (mbsf) with a recovery of 185.2 m (56%) of sediment and igneous rock. In total, Hole U1575A penetrated 122.4 m of igneous basement. Coring was terminated to realize the remaining major objectives of the expedition. A total of 137.0 h, or 5.7 days, were spent on Hole U1575A.

Principal Results

Sedimentology

The sedimentary cover at Site U1575 includes three lithostratigraphic units, which consist of a thick Pleistocene to late Miocene succession of unconsolidated calcareous nannofossil-foraminifera ooze (Lithostratigraphic Unit I; 0–194.10 mbsf) and a much shorter Miocene to Upper Cretaceous succession of poorly lithified nannofossil-foraminifera chalk with clay (Lithostratigraphic Units II and III) to the bottom of the sedimentary succession above the igneous basement (Unit IV) at 209.92 mbsf. The contact between the sedimentary cover and the uppermost lava in the basement (Igneous Lithologic Unit 1) was not recovered, but sedimentological observations and preliminary shipboard biostratigraphic and paleomagnetic data do not suggest the existence of a significant time gap between the deposition of the lavas and the overlying sedimentary sequence. Consistent with an increase in sediment consolidation downhole, core recovery increases from ~52% in Unit I to ~73% in Unit III.

Unit I consists of a ~195 m thick succession of white nannofossil-foraminifera ooze with minor radiolarians that represents Pleistocene to Pliocene pelagic sedimentation. Subtle gray and, more rarely, white to green centimeter-sized banding occurs throughout due to accumulations of pyrite framboids and possibly Fe-Mn-rich particles. The succession becomes pale brown in the lowermost 10 m of the unit, reflecting a minor increase in the clay content.

Unit II is a much thinner (<10 m) late Miocene to early Oligocene succession between 194.10 mbsf and 198.56 mbsf, consisting of a brown nannofossil-foraminifera chalk with minor radiolarians and clays. The chalk is commonly bioturbated and includes subtle white to pale brown color changes controlled by the relative abundance of calcareous (mostly biogenic) components and clays at the centimeter to subcentimeter scales. Rare microscopic particles of palagonite and volcanic minerals of unknown provenance were also observed. Concentrated foraminifera bands and parallel to cross-bedded laminae in the chalk likely indicate local winnowing and reworking by bottom currents.

Unit III represents a ~10 m thick, Campanian sequence (198.56–209.92 mbsf) of predominantly consolidated brown to pink nannofossil-foraminifera chalk with rare to minor radiolarians and clays. Bioturbated chalk intervals are interrupted by winnowed bioclastic sand with parallel to cross-bedded laminae and, more rarely, normal to inverse grading. Volcaniclastic deposits are rare and consist of altered volcanic glass, ferromagnesian and Fe-oxide minerals and feldspars. These clasts are mixed with a dominant bioclastic fraction composed of foraminifera and fragments of inoceramid shells. Rare fragments of red algae were encountered, which suggest deposition of the sequence at <300 m depth and/or sediment reworking from a nearby shoal. These observations support pelagic sedimentation under the influence of bottom currents and possibly low-density turbidity currents.

Few structural features were observed in the sedimentary succession above the igneous basement of Unit IV. Several intervals of tilted bedding occur in Units II and III. The apparent dips of these tilted beds in Unit II are around 11°, whereas those in Unit III are higher, averaging around 39°. Two thick intervals (~30 cm) of sedimentary dikes formed above tilted beds in Unit III, where sediments are strongly disturbed and mixed with coarse angular grains.

Sedimentary deposits are also present intercalated with the lava succession in the igneous basement (Unit IV). In the upper part of the basement, the sedimentary deposits consist of white azoic to nannofossil-bearing micrite that occurs in layered infills of cavities and cracks between and within the lavas. Further downhole, below the lower pillow lava package, there are similar thin intercalations deposited during hiatuses in volcanic activity.

Igneous Petrology and Volcanology

Hole U1575A penetrated 122.4 m of basement, recovering 71.6 m of igneous rock (58.5%). This basement was divided into 10 units, beginning with a succession of four massive submarine flows. Overall, the eruptive style comprised an alternating sequence of submarine lavas involving massive flows (up to 21 m thick), individual sheet flows, and stacks of pillow and lobate lavas. All these volcanic units consist of aphanitic to intersertal to holocrystalline basalt with phenocysts and glomerocrysts of plagioclase (3%–15%) and clinopyroxene (1%–5%). Olivine is sparse and only intermittently present (0%–3%), being completely altered in ~50% of the lavas. The igneous lithological units show significant overlap in mineralogy but may be summarized as follows: Massive flow Subunits 1a/b (8.04 m thick) and 2a/b (18.08 m thick) consist of pairs of highly plagioclase-pyroxene ± olivine phyric, holocrystalline basaltic lava flows separated by a glassy margin. Subunits 3a–d present a change of eruptive behavior and consist of 12.87 m of intercalated succession of sheet flows, lobate flows, and pillow lavas (i.e., "pillow lava stack"). Modal compositions vary from sparsely to highly plagioclase-pyroxene-olivine phyric. Basaltic glass and altered aphanitic material are found in pillow rims and flow boundaries. Unit 4 is a 10.69 m massive basalt flow with sparse to moderate plagioclase and pyroxene phenocryst abundance, including sparse olivine. Underlying Unit 5, a thick (15.00 m) succession of pillow lavas, shows numerous glassy margins. Phenocrysts consist of plagioclase and pyroxene with trace amounts of olivine, and the groundmass ranges from glassy to aphanitic to holocrystalline. Units 6 to 9 range from massive flows (Unit 6 = 4.01 m and Unit 8 = 21.08 m) to thinner underlying pillow lavas (Unit 7 = 4.05 m and Unit 9 = 1.92 m). Mineralogy varies from sparsely to moderately plagioclase-pyroxene phyric, lacking olivine. This sequence erupted onto a nannofossil-foraminifera chalk substrate which is partially preserved at its base and in pillow lobe interstices as disturbed and deformed material. At the bottom of Hole U1575A, Subunits 10a (5.06 m) and 10b (13.31 m) consist of one massive flow each, separated by chilled margins. They are moderately phyric, consisting of variable proportions of plagioclase, pyroxene, and olivine with glomerophyric and holocrystalline textures. Alteration in the igneous basement is due to ambient low-temperature seafloor processes. Oxidative alteration likely occurred shortly after eruption as cooling lava units were subjected to seawater ingress, aided by the development of cooling fractures in the brittle outer flow crust, leading to calcite precipitation in fractures. Alteration intensity is slight to occasionally moderate throughout, with centers of thicker flows presenting near-fresh primary minerals (except for olivine). Low-temperature alteration is also reflected by carbonate vein networks, which vary in thickness and orientation. These veins are frequently observed in the uppermost 20 m of the volcanic succession of Unit IV, with decreasing abundance downhole. In the entire igneous basement, the degree of overall alteration correlates positively with the abundance of carbonate veins.

Biostratigraphy

Detailed calcareous nannofossil and planktonic foraminifera biostratigraphy was performed on core catcher samples recovered from Hole U1575A. Microfossil examination provided a preliminary chronostratigraphic framework for sediments at Site U1575. First occurrence and last occurrence datums were largely based on Gradstein et al. (2020).

The sediment succession at Site U1575 spans the Pleistocene to Upper Cretaceous (upper Campanian) time interval (0.43–78 Ma). An almost continuous Pleistocene to Pliocene pelagic sediment succession was recorded in Lithostratigraphic Unit I, ranging from 0.43–4.50 Ma (possibly excluding the earliest Pliocene [Zanclean]). Key taxa for this time interval for calcareous nannofossils are *Pseudoemiliania lacunosa*, *Helicosphaera sellii*, *Discoaster tamalis*, and *Amaurolithus primus*. Key taxa of planktonic foraminifera for this interval are *Globorotalia hessi*, *Globorotalia crassaformis*, and *Globorotalia margaritae*. Uncertainties in the assignment of the Pliocene/Miocene boundary have been noted based on shipboard examination and will require higher resolution studies to verify this boundary. The interpretation of the Miocene interval in Lithostratigraphic Unit II was more complex due to possible hiatuses, poor recovery, and the presence of mixed assemblages. A tentative biostratigraphic framework places this part of the sequence in the upper Miocene and further postexpedition investigation is required. From Sections U1575A-20R-CC to 21R-CC, Unit II shows a time gap and extends to the lowest Oligocene (Rupelian) as detected by the occurrence of calcareous nannofossil *Reticulofenestra umbilicus* in Section 21R-CC. Further downhole, a major unconformity separates early Oligocene and late Campanian flora and fauna recorded within Lithostratigraphic Unit II and Lithostratigraphic Unit III, respectively, with the latter being the lowermost part of the cored sedimentary succession. The maximum age detected is ~78 Ma (Section 20R-CC) based on the occurrence of *Eiffelithus eximius* and *Uniplanarius sissinghii*, along with the absence of *Uniplanarius trifidus* nannofossil taxa. Samples were taken from thin sediment layers interbedded with lava flows within the igneous basement (Lithostratigraphic Unit IV), but preliminary age determination will require postexpedition analysis.

Paleomagnetism

Sediments recovered at Site U1575 are weakly magnetic (ranging from 10^{-6} to 10^{-3} A/m) for Cores U1575A-1R through 20R (0–194.1 mbsf). As such, both the superconducting rock magnetometer (SRM) and JR-6A spinner magnetometer failed to produce reliable directions and no magnetostratigraphy could be determined for this interval. Lithified basal sediments from Cores 21R through 22R had stronger magnetizations (ranging from 10^{-3} to 10^{1} A/m). Several intervals within the basal sediments, however, exhibited pervasive tilting, precluding determination of a robust magnetostratigraphy for Cores 21R and 22R. Nevertheless, we interpret Sections 22R-4 and 22R-5 to represent reversed polarity Chron 32r.

Igneous rocks recovered at Site U1575 are characterized by low unblocking temperatures (~150–450°C) and median destructive field values ranging from ~5–125 mT. These unusually high coercivity values are likely caused by the presence of dendritic iron oxides (most likely titanomagnetite or titanomaghemite), which can exhibit strong magnetic anisotropy. These phases were observed in thin sections of Hole U1575A igneous rocks. Thermal demagnetization of some discrete samples showed evidence of possible partial self-reversal of magnetization. All samples subjected to alternating field (AF) demagnetization displayed a drill string overprint that was typically removed by 20 mT, before revealing a unidirectional origin-trending component. Magnetic inclinations obtained by principal component analysis from discrete samples agree well with inclinations associated with the 20 mT AF demagnetization step in SRM data acquired from core archive section halves at corresponding depths. Nearly all measurements are of normal polarity, consistent with basement formation during the Cretaceous Normal Superchron (C34n).

Geochemistry

At Site U1575, interstitial water samples were analyzed for pH, alkalinity, major cation and anion concentrations, and trace element concentrations. An alkalinity maximum was identified at the depth of 15 mbsf. Slightly below this depth, at 25–30 mbsf, maxima for Ca, K, Sr, and Si, and minima for Mg and Li concentrations were observed. These features are attributable to diageneses of biogenic carbonates and silica. A Mn reduction interval was found at the shallow depth of 10 mbsf. Due to the hiatus between Lithostratigraphic Units I and II, no signs of interaction between basaltic basement and Lithostratigraphic Unit I were observed, and profiles of many elemental concentrations remained uniform between 50 and 200 mbsf. Sediment samples were also analyzed to determine the content of $CaCO_3$, total carbon, and total organic carbon. In Lithostratigraphic Unit I (dominantly nannofossil-foraminifera ooze), the $CaCO_3$ content ranges from 93 to 98 wt%. In Lithostratigraphic Units II and III, the $CaCO_3$ content declines to 85 and 74 wt%, respectively. Methane concentrations measured from the headspace gas are at the atmospheric background level (lower than 2.0 µL/L).

For the determination of major and trace element concentrations in recovered volcanic rocks, representative samples obtained from the igneous basement were analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) and portable X-ray fluorescence spectrometry (pXRF) on both rock powders (n = 33) and surfaces of archive half section rock pieces (n = 267). Overall, the comparison of the ICP-AES and pXRF results of the same samples displays excellent to good correlation. The loss on ignition (LOI), a common indicator for the degree of alteration, is relatively low overall for such old submarine rocks (LOI < 3 wt%). Nevertheless, K and Sr enrichment due to seawater interaction and olivine alteration affect the composition of the analyzed lavas to variable degrees, which has also been documented by petrographic investigations. All igneous rock samples are basalts and have Ti/V values similar to mid-ocean ridges or oceanic plateaus, consistent with interaction of the Tristan-Gough-Walvis hotspot with the Mid-Atlantic Ridge. Downhole geochemical variations display an overall increase in MgO, possibly reflecting increasing differentiation of the magma reservoir with decreasing age. The most striking geochemical variability was observed at ~274 mbsf. In the upper portions of the recovered interval, the TiO_2 content is relatively constant and sharply drops at 274 mbsf at the bottom of Igneous Lithologic Unit 5. Thereafter, the TiO_2 value remains constant throughout Unit 5 to Unit 8 and slowly increases from Unit 9 to 10 again, to a concentration similar to the upper part of the volcanic sequence (Units 1–5). This Ti evolution correlates with a similar pattern for Sr, Y, and Zr. Another geochemical anomaly was identified around 255 mbsf in the lower part of Subunit 4a, which shows an enrichment of TiO_2, Ni, and Cu. Also, Subunits 10a and 10b may be distinguished by differing Ni content.

Physical Properties

Physical properties measurements were made on recovered whole-round and section half cores as well as discrete cube and wedge samples, indicating three distinct units: (1) calcareous ooze, (2) chalk, and (3) basalt, corresponding to the established lithostratigraphic units. Within the sedimentary succession, natural gamma radiation (NGR) and magnetic susceptibility (MS) peaks at ~194 mbsf correlate to the calcareous ooze-chalk contact: mean NGR values increase from 3.3 to 16.0 counts/s and average MS (reported in instrument units) increases from 1.0 to 38.1. The transition from the sedimentary overburden to igneous basement is imaged at ~210 mbsf by gamma ray attenuation (GRA), moisture and density (MAD) bulk density and NGR average values. Bulk density increases from 1.73 to 2.59 g/cm^3 (GRA) and from 1.89 to 2.85 g/cm^3 (MAD), respectively, while NGR decreases from 8.68 to 3.20 counts/s across the sediment-basement interface. Intervals of low whole-round core and archive half section surface point MS values appear to correlate with intervals of highly fragmented basalt, while higher values (~1,000 to ~3,000, both instruments) appear to be associated with intervals of coherent (>20 cm length) basalt core pieces. These trends are consistent with GRA bulk density and NGR measurements from the same intervals. However, anomalously high MS and NGR values in a rubbly zone appear to correspond to a shift from high- to low-TiO_2 concentrations in the volcanic sequence at ~270 mbsf.

References

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.