IODP Expedition 391: Walvis Ridge Hotspot

Site U1576 Summary

Background and Objectives

Site U1576 (proposed Site VB-14A) is located on the middle west flank of Valdivia Bank, the broad, oceanic plateau that is part of Walvis Ridge. The site was chosen to obtain samples from buried igneous basement in a location that can only be sampled by drilling. Valdivia Bank represents a poorly understood edifice of the Walvis Ridge that may have formed by interaction with the Mid-Atlantic Ridge or a microplate that formed by a plate boundary reorganization. Radiometric age dating is planned to determine the age of igneous basement at this site. Along with other drill site sampling of Valdivia Bank, age dating will enable us to test whether there is a north-south age progression, as predicted by hotspot models, or an east-west age progression as predicted by spreading ridge formation models. The petrology and geochemistry of the basement basalt samples should elucidate the petrogenesis and mantle sources of these magmas, including whether the isotopic zonation observed at the Deep Sea Drilling Project (DSDP) Leg 74 transect, a few hundred kilometers to the southwest, continues to Valdivia Bank. Paleomagnetic data from sediment and basalt samples will help determine the paleolatitude of the hotspot during the late Cretaceous. Sediments recovered at Site U1576 will help constrain the age and evolution of the plateau and provide insights into the paleoenvironmental trends of the midwater column of the South Atlantic.

Operations

Two holes were drilled at Site U1576. Hole U1576A is located at 24°35.7520′S, 5°7.3163′E in a water depth of 3032.3 m as obtained from the precision depth recorder (PDR). In Hole U1576A, we used the rotary core barrel (RCB) coring system to advance from the seafloor to a final depth of 398.1 m below seafloor (mbsf) with a recovery of 309.3 m (78%) of sediment and igneous rock. After attempts failed to clear a plug in the outer core barrel and bit at the bottom of the hole, it was decided to abandon Hole U1576A and offset the drilling 400 m along the site survey seismic line at an orientation of 095°, in order to start a new hole (U1576B). A total of 76.25 h, or 3.2 days, were spent on Hole U1576A. In Hole U1576B, located at 24°35.7711′S, 5°7.5513′E in a water depth of 3027.2 m, as obtained from the PDR, we first drilled without core recovery from the seafloor to 365.0 mbsf. Then, the RCB coring system was deployed to advance from 365.0 mbsf to a final depth of 450.3 mbsf with a recovery of 66.3 m (78%) of sedimentary and igneous rock. Coring was terminated early to complete the remaining major objectives of the expedition. In total, Holes U1576A and U1576B penetrated 17.9 m and 64.9 m of igneous basement, respectively. The total time spent on Hole U1576B was 78.75 h, or 3.3 days. Overall, we spent 155.0 h, or 6.5 days, at Site U1576.

Principal Results

Sedimentology

The sedimentary succession at Site U1576 is divided into four lithostratigraphic units. It consists of an ~380 m thick succession of ooze and chalk on top of a volcanic basement, and six intercalations of chalk in the volcanic basement for an additional cumulated sediment thickness of ~40 m. Two holes were drilled at Site U1576. Hole U1576A recovered the sedimentary cover from 0 to 380.18 mbsf. Hole U1576B recovered the lower ~20 m of this sedimentary cover from 365.00 to 380.18 mbsf, and then six sedimentary intervals in the volcanic basement down to 441.36 mbsf. Excellent lithostratigraphic correlation was found in the lower ~20 m of the sedimentary cover retrieved at the two holes. The sedimentary cover is divided into four main lithostratigraphic units of ooze (Lithostratigraphic Unit I) and chalk (Lithostratigraphic Units II–IV) that were deposited on top of the volcanic basement between the Pleistocene and early Campanian. Drilling disturbance is present throughout the ooze of Unit I, but is commonly restricted to the outermost edges of the cores with uparching of the bedding (i.e., beds form an inverted "U"). Increased consolidation in the chalk of the underlying Units II to IV allowed better preservation of sedimentary detail with only local "biscuiting" and minor uparching of the bedding. Core recovery ranges from ~75% in Unit I (0–96.83 mbsf) to ~89% in Unit II (96.83–124.71 mbsf) and Unit III (124.71–322.19 mbsf), and ~52% in Unit IV (322.19–380.18 mbsf in Hole U1576A, 365.00–385.28 mbsf in Hole U1576B).

Unit I is a 96.83 m thick sequence of unconsolidated nannofossil-foraminifera ooze and nannofossil ooze with foraminifera, locally with clay and minor radiolarians, which records pelagic sedimentation between the Pleistocene and middle Miocene. Three subunits were defined in Unit I based on distinct brownish color correlated with minor changes in clay content. The lower boundary of the unit is marked by a sharp contact with brown-pink calcareous ooze/chalk with clay in underlying Unit II.

Unit II represents an ~28 m thick sequence of unconsolidated to consolidated pale brown to brown foraminifera-nannofossil ooze/chalk with clay and minor radiolarians, which records pelagic sedimentation during the Paleocene. The base of the unit corresponds to the occurrence of a distinctive ferromanganese crust at the top of underlying Unit III, which likely represents a significant reduction, or pause in ooze accumulation very close to or at the Cretaceous/Paleogene (K/Pg) boundary. Unit II is almost exclusively composed of layered, slightly to heavily burrowed foraminifera-nannofossil ooze/chalk with clay, with regular color changes that form approximately 10–50 cm thick cycles with more prominent burrowing in the darker intervals. A minor fraction (<1% volume) of the unit consists of partly disaggregated layers and beds of well-sorted foraminifera to volcanic sand, of which the nature and origin(s) remain poorly constrained due to drilling disturbance. These beds could represent winnowing of the ooze by bottom currents as well as volcaniclastic deposition by turbidites and/or tephra fallout.

Unit III consists of an ~197 m thick sedimentary succession predominantly composed of well-defined cyclical white and reddish-brown or greenish-gray foraminifera-nannofossil chalk with clay, which records pelagic sedimentation between the Maastrichtian and the Campanian. Two subunits (IIIA and IIIB) were defined in Unit III based on progressive attenuation of reddish-brown coloring of the chalk and its replacement by greenish-gray color, which may correspond to a transition from predominantly oxidative to predominantly reducing conditions on the seafloor starting at ~275 mbsf (~middle Campanian). The base of the unit is marked by almost complete attenuation/replacement of the reddish-brown color downhole and the first appearance of thin cm-sized bands of dark green siliceous chalk in underlying Unit IV. Similar to overlying Unit II, the chalk of Unit III is interbedded or mingled with sparse volcanic to calcareous sand. These are commonly laminated and normally graded, and are considered to represent infrequent bottom and/or turbidity currents. Unit III is also characterized by sparse, thin layers of altered ash that are interpreted as distal tephra deposits preserved during periods of low sedimentation and/or bioturbation in the pelagic sediment.

Unit IV is an ~20 m (Hole U1576B) to ~58 m (Hole U1576A) thick sedimentary sequence (322.19–380.18 mbsf in Hole U1576A, 365.00–385.28 mbsf in Hole U1576B), which is predominantly composed of light green to darker gray foraminifera-nannofossil chalk with clay and locally faint nuances of pinkish-gray intervals. Similar to overlying Subunit IIIB, the chalk represents pelagic sedimentation in anoxic conditions during the early Campanian, possibly reflecting cyclical sedimentation. Calcareous and volcanic sandy deposits similar to those observed in Units II and III become slightly more important in Unit IV, forming a total of 5% of the recovered sediment. The lower boundary of Unit IV corresponds to the inferred (i.e., not recovered) contact with the underlying igneous succession (Unit V) in Holes U1576A and U1576B. The correlation of Unit IV between Holes U1576A and U1576B is further established by the occurrence of an ~1.61 m thick matrix-supported calcareous conglomeratic deposit, which defines a clear stratigraphic marker ~18.2 and 16.0 m above the igneous basement in Holes U1576A and U1576B, respectively. This lithology and other calcareous clastic deposits record a turbidite-rich interval in Unit IV. Tilted beddings observed in Unit IV usually show low apparent dip angles of less than 10°. Apparent angles of up to ~55° are occasionally present close to the sediment/basement contact.

Seven sedimentary intervals (S1–S7) of variable thickness (~0.8–11.7 m) recovered as intercalations within the volcanic basement in Hole U1576B are a downhole continuation of the lithologies retrieved in the lower sedimentary cover above the uppermost basalt lava (Unit IV). Sedimentation is similarly dominated by pelagic deposition of gray bioturbated foraminifera-nannofossil chalk with clay, with thin interbeds of calcareous to volcaniclastic turbidites. Locally, lava-sediment interaction led to formation of peperites and hydrothermal alteration of both basalt and sediment. A submeter interval of metalliferous sedimentation occurs at ~420 mbsf between lavas, which similarly suggests nearby synvolcanic hydrothermal activity on the seafloor. Intervals of significant deformation were found in two sediment interbeds. Healed fractures and tilted beddings show various dipping angles. Both normal and reversed faults

occur. Deformation structures include conjugate normal faults as well as en echelon and downward splaying normal faults.

Igneous Petrology and Volcanology

Igneous rocks were recovered in both Hole U1576A and Hole U1576B. The igneous basement at Site U1576 represents Lithostratigraphic Unit V in the overall subseafloor succession, and the two holes are stratigraphically correlated. Hole U1576A penetrated 12.62 m of igneous basement, with 7.56 m recovered (~60% recovery) consisting entirely of basalt. Two igneous units have been identified in Hole U1576A. The first unit is a sheet flow (1.97 m) and the second unit consists of pillow basalt, in which the hole terminates at 10.65 m cored thickness. The lavas range from glassy and aphanitic to holocrystalline and intersertal. Fresh glass is present in the pillow sequence and on the tops of some sheet flows. The lavas are slightly vesicular with small (~1 mm) round vesicles and, when phenocrysts are present, are highly phyric (plagioclase = 9%–12%; clinopyroxene = 6%–8%). Hole U1576B penetrated 64.9 m of igneous basement, with 51.48 m recovered (~79% recovery), consisting of 32.79 m of basalt and 18.69 m of intercalated chalk and turbidite horizons. Hole U1576B terminates within a sheet flow with a minimum thickness of 2.56 m. Eleven igneous units have been identified in Hole U1576B, comprising pillow, sheet, and massive lava flows, with cumulative total drilled thicknesses of 18.16 m, 2.56 m, and 20.02 m, respectively. The top basaltic unit consists of completely altered pillow basalt lava flows that correlate to the pillow basalts at the base of Hole U1576A. Units 1–3 (pillow lava flows) and 4–5 (massive lava flows) represent aphyric basalts with plagioclase microphenocrysts occurring occasionally. Units 6–11 (one massive flow, one sheet flow, and several pillow basalt flows) are sparsely plagioclase ± clinopyroxene phyric (2%–4% total phenocrysts). Massive and sheet flows contain both plagioclase and clinopyroxene glomerocrysts and phenocrysts in an intersertal groundmass, showing higher phenocryst abundances (8%) in the center of the flows. Pillow lavas contain plagioclase and clinopyroxene microlites and small glomerocrysts in their glassy rims. Olivine occurs infrequently (<1%) and is completely altered. Seriate textures are common in massive lava interiors, whereas clear porphyritic textures are found closer to flow boundaries. Fresh glass is present at some flow margins, but it is mostly altered and replaced by clay minerals. The lavas are dominantly nonvesicular to sparsely vesicular, except for the pillow lavas of Unit 2 being moderately to highly vesicular with vesicles filled by secondary minerals. Alteration in the basalt lava successions in both holes at Site U1576 is significant and pervasive at the tops and bottoms of lava flows and throughout the interiors of small flows; only the larger massive flow cores contain near-fresh igneous minerals. Chemically reduced hydrothermal fluids dominate alteration processes, which caused a pale green discoloration and formation of secondary pyrite in vesicles and in the groundmass. This alteration is distinctive from the pale reddish-tan color associated with the oxidative alteration at Site U1575. Alteration-derived veins that crosscut each other are common within the recovered volcanic sequence, indicating multiple phases of hydrothermal fluid percolation.

Biostratigraphy

Detailed calcareous nannofossil and planktonic foraminifera biostratigraphy was performed on 39 and 16 core catcher (CC) samples, respectively, from the continuous sediment successions of Hole U1576A and Hole U1576B. Five additional core catchers were analyzed for calcareous nannofossils from the interbedded sediments recovered in Hole U1576B. CC samples were analyzed for first occurrence and last occurrence datums, which were based on Gradstein et al. (2012, 2020). Nannofossil and foraminifera datums showed good agreement throughout the cored sediment sequence. Biostratigraphic analysis revealed a succession of Pleistocene through lower Miocene (Lithostratigraphic Subunits IA–IC) sediments that is likely incomplete. Additional analysis of these units will be required to determine where and how much time is encompassed within the potential hiatuses. A large hiatus/unconformity is observed between the oldest Miocene-aged sediments (Langhian) in Section U1576A-10R-CC and lower Paleocene (Danian) sediments recovered from Section 11R-CC, suggesting that the Lithostratigraphic Unit I/II boundary corresponds to a major ~45 My hiatus in the upper part of the Hole U1576A sediment succession, with both the Oligocene and Eocene missing from retrieved cores. Sediments recovered below the unconformity revealed an apparent continuous section from the lower Paleocene (Danian) through the Upper Cretaceous (Maastrichtian/Campanian). This succession likely contains the K/Pg boundary and will be closely analyzed by postexpedition research to determine its exact placement within the cored sequence. The lower part of the sediments provided a maximum early Campanian basement age of approximately 79.00–81.38 Ma. Interbedded sediments recovered from Hole U1576B revealed only Campanian ages. These interbeds likely represent an older continued succession of the basement interval recovered from Hole U1576A, with most samples assigned to lower Campanian biozones.

Paleomagnetism

Cores U1576A-1R through 10R from Hole U1576A are primarily composed of weakly magnetic (ranging from 10^{-6} to 10^{-3} A/m) unconsolidated calcareous nannofossil ooze. As such, both the superconducting rock magnetometer and JR-6A spinner magnetometer failed to produce reliable directions and no magnetostratigraphy could be determined for this interval. Lithified sediments were recovered from Cores U1576A-11R through 39R and Sections U1576B-2R-1 through 5R-3. These lithified sediments have stronger magnetizations (ranging from 10^{-5} to 100 A/m) and produced higher quality magnetic measurements, which permitted development of a robust magnetostratigraphy for these intervals. Demagnetizations carried out on discrete samples agree well with half-round measurements and suggest that magnetization is carried by a mixture of magnetite and hematite. For Hole U1576A, we identified 14 polarity chrons that span from the Danian (Chron 26r in Core U1576A-11R) to the early Campanian (Chron 33r near the contact with igneous basement). We assigned polarity chrons for sedimentary cores from Hole U1576B that were consistent with polarity chrons from Hole U1576A. Sections U1576B-2R-1 through 4R-2 are of normal polarity and consistent with normal Chron 33n. These are underlain by sedimentary Sections U1576B-5R-1 through 5R-3, which contact basement and exhibit reversed polarity consistent with Chron 33r. There were no major gaps identified in the magnetostratigraphy in the Paleocene and older sediments.

Igneous rocks recovered from Site U1576 span Cores U1576A-40R through 41R and Cores U1576B-5R through 17R. These cores consist of basalts with interbedded chalk between flows. Some of the basalts are considerably altered, particularly close to contacts with sediment interbeds, changing their magnetic characteristics. Magnetic intensities range from 10^{-5} to 10^{-2} A/m in the sediment interbeds and heavily altered basalt, and 1 to 10 A/m in the mostly unaltered basaltic sections. Nearly all igneous cores display a reversed polarity magnetization after AF cleaning to 20 mT, which is compatible with the reversed polarity chron assignment of 33r observed in the top of the igneous basement. Most of the igneous rocks are characterized by unblocking temperatures between 200° and 550°C and median destructive field values around 20 mT. The large range of magnetization unblocking temperatures is most likely related to the presence of titanomagnetite with varying Ti concentrations.

Geochemistry

At Site U1576, interstitial water (IW) samples from Hole U1576A were analyzed for pH, alkalinity, and concentrations of major cations, anions, and trace elements. Both alkalinity and pH peaked within Lithostratigraphic Subunit IIIA. Across the entire sedimentary succession, we observe linear increases in IW calcium and lithium concentrations, and linear decreases in IW magnesium and potassium concentrations. Two maxima of IW silicon concentration, near the top of the sediment and at the bottom of the sediment succession, are attributable to dissolution of biogenic silica and volcanic sands, respectively. A broad IW manganese peak, found from Lithostratigraphic Subunit IC to the upper part of Lithostratigraphic Subunit IIIA, indicates the presence of a manganese reduction interval in the upper part of sediment succession. In general, IW geochemistry at Site U1576 is affected by diagenetic processes of calcite, silica, and organic matter, as well as interactions of IW with basaltic basement and volcanic sands. Sediment samples were also analyzed for the content of $CaCO_3$, total carbon, and total organic carbon. $CaCO_3$ content remains high across Lithostratigraphic Subunit IA to IIIA and declines in Lithostratigraphic Subunit IIIB and Unit IV as the content of clay increases. Methane concentrations measured from the headspace gas are lower than the atmospheric background level of 2.0 µL/L.

At Site U1576, two samples from Hole U1576A and 10 samples from Hole U1575B were analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) on powders and by portable X-ray fluorescence (pXRF) on 103 archive half section pieces of the recovered cores for the determination of major and trace elements. Even though the least altered recovered sections of the distinct lithologies were analyzed, several samples were affected by varying degrees of alteration as demonstrated by scattered concentration data of fluid-mobile elements (e.g., K). The analyzed rocks from Hole U1576A are classified solely as basalts, whereas the recovered rocks from Hole U1576B range from basalt to basaltic andesite. The Ti-V composition of all samples from Site U1576 is similar to mid-ocean ridge basalts and ridge-centered ocean island basalts. Interestingly, V and TiO_2 are well correlated at both Site U1575 and Site U1576, but the trend is shifted, and Site U1576 has a slightly lower V concentration at a given Ti content. On bivariate diagrams with MgO versus the other major oxides and trace elements, the

Site U1576 rocks lie generally within the compositional array of the previously reported dredge and DSDP site samples from Walvis Ridge of the Tristan-Gough hotspot track. Two igneous lithologic units were distinguished in Hole U1576A and 11 units in Hole U1576B. Based on the lithology and geochemical composition, the second unit of Hole U1576A and first unit of Hole U1576B appear to be indistinguishable and represent most likely the same pillow lava flow stack. Therefore, 12 distinct igneous lithologic units are present within the combined volcanic succession at Site U1576. Geochemical downhole variation using pXRF and ICP-AES analysis shows that all lavas in both holes at Site U1576 have high TiO_2 concentration, contrasting with Site U1575, which contains lavas with both high and low TiO_2 contents.

Physical Properties

Physical properties measurements were made on 93 cores from Holes U1576A and U1576B. Natural gamma radiation (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) bulk density, *P*-wave velocity, porosity, and thermal conductivity measurements reveal a relatively simple succession of sedimentary and volcanic units in Hole U1576A: calcareous ooze grading into more cohesive chalk and limestone from the seafloor to ~380 mbsf, and relatively altered basalt flows and pillows to the bottom of the hole at ~392 mbsf. In Hole U1576B, the same suite of measurements recorded a more complex sequence of interbedded sediment and basalt units below the initial sediment-basement contact at ~385 mbsf to the bottom of the hole at ~451 mbsf. Localized features within the sedimentary and volcanic intervals of both holes are also reflected by physical properties data sets, specifically NGR and MS. In Hole U1576A, the highest MS (325×10^{-5} SI) recorded in the sediment interval correlates to an ~4 cm thick turbidite or altered tuff at ~135 mbsf (Section U1576A-15R-1), and at the same depth, NGR abruptly increases to 22.2 counts/s from a background range of ~6–8.5 counts/s. Other high MS and NGR peaks within the sediment interval each correlate to an ~2 cm turbidite or altered tuff layer at ~98 mbsf (MS of 150×10^{-5} SI; NGR of 10.1 counts/s; Section U1576A-11R-3) and at ~123 mbsf (MS of 145×10^{-5} SI; NGR of 18.8 counts/s; Section U1576A-13R-6), respectively. In Hole U1576A, peaks in NGR, MS, and Section Half Multisensor Logger logs align with discrete turbidite or altered tuff layers from ~95–280 mbsf, and all three datasets display a broad cyclical trend over the same interval. In Hole U1576B, MS values are uniformly low in the upper chalk layer and interbedded limestones, with an overall mean value of $15.8 \pm 24.8 \times 10^{-5}$ SI, but NGR counts in interbedded chalk and limestone below the uppermost sediment-basalt contact increase with depth from 4.31 counts/s at 387 mbsf to 30.2 counts/s at 441 mbsf. Basalt layers in Hole U1576B show an increase in MS to an overall mean of $986 \pm 171 \times 10^{-5}$ SI. Relatively high NGR and MS values in Hole U1576B may be related to pervasive alteration in interbedded sedimentary and basalt units. Similar trends in MS and GRA bulk density values at ~371 mbsf (MS = 8.55×10^{-5} SI; NGR = 18.5 counts/s) in Hole U1576A and at ~374 mbsf (MS = 8.84×10^{-5} SI; NGR = 18.8 counts/s) in Hole U1576B correlate to a turbidite or altered tephra layer at the same depth in each hole. This correlation suggests that Holes U1576A and U1576B may sample a common stratigraphic sequence from the seafloor to ~451 mbsf at Site U1576.

References

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