IODP Expedition 391: Walvis Ridge Hotspot

Site U1577 Summary

Background and Objectives

Site U1577 (proposed Site VB-13A) is located on the extreme eastern flank of Valdivia Bank as a complement to Sites U1575 and U1576 on the western and northern sides of the edifice, respectively. The site was selected to recover igneous basement samples from a buried part of the plateau to understand its geologic and geochemical evolution in a location that can only be sampled by drilling. Samples from Site U1577 will help determine whether the isotopic zonation, observed several hundred kilometers farther southwest in the Tristan-Gough-Walvis hotspot track, is found at Valdivia Bank. Geochronology studies of basalts from Site U1577, along with those from other Valdivia Bank sites, will constrain the temporal evolution of the plateau. Specifically, is there a north-south age progression, as predicted by hotspot models, or is the progression east-west, as predicted by spreading ridge formation? Paleomagnetic studies of Site U1577 basalts will add to those from other sites to examine the paleolatitude of the hotspot during the Late Cretaceous time. Studies of the sedimentary overburden will add to those from previous sites to understand the sedimentary and paleoenvironmental history of Valdivia Bank.

Operations

A single hole was drilled at Site U1577. Hole U1577A is located at 25°12.1439′S, 7°29.8140′E at a water depth of 3940.2 m as obtained from the precision depth recorder. In Hole U1577A, we used the rotary core barrel coring system to advance from the seafloor to a final depth of 193.9 m below seafloor (mbsf) and recovered 152.9 m (79%) of sediment and igneous rock. In total, Hole U1577A penetrated 39.1 m of igneous basement. Coring was terminated early to complete the remaining major objectives of the expedition. The total time spent on Hole U1577A was 109.5 h, or 4.6 days.

Principal Results

Sedimentology

The sedimentary deposits at Site U1577 are divided into three lithostratigraphic units that range in age from Paleocene (Thanetian) to Late Cretaceous (latest Santonian). It consists of an ~155 m thick succession of nannofossil ooze and chalk with variable contents of clay and volcanic tephra. This sedimentary succession overlies the igneous basement, which consists of three massive lava flows (4, 12, and 19 m in thickness) devoid of sedimentary intercalation or infillings. The lithostratigraphic subdivision was defined based on macroscopic and microscopic lithological observations, supplemented with changes in natural gamma radiation (NGR), and biostratigraphic data. Three units of pelagic sediment with a minor component of tephra layers were defined (Units I, II, and III). Sediment consolidation increases gradually downhole, with ooze dominant in the uppermost Unit I and chalk dominant in underlying Units II and III. Drilling disturbance occurs throughout the ooze of Unit I where the cores commonly display uparching of the bedding (i.e., beds form an inverted "U"). The increased consolidation in the sediment deeper in the hole offers better preservation of sedimentary detail, with disturbance limited to less consolidated intervals where localized "biscuiting" and minor uparching of the bedding occur. Consistent with the increase in sediment consolidation downhole, core recovery ranges from ~69% in Unit I (0–46.90 mbsf) to ~90% in Unit II (46.90–70.72 mbsf), and is ~82% in Unit III (70.72–154.80 mbsf).

Unit I is a 46.90 m thick Paleocene succession of unconsolidated pale brown to white bioturbated nannofossil ooze with clay. It is irregularly interbedded with minor, brown altered volcanic ash layers containing sparse crystals of feldspar, biotite, and amphibole. A marked decrease in clay content and tephra abundance occurs between ~11 and 24 mbsf, producing an interval of distinctively lighter sediment. The more clayey ooze intervals at the top and bottom of the unit display light brown to brown 10–50 cm thick cycles, with the lowest 3–4 m having an increasingly pink hue and showing ferromanganese layers disaggregated by drilling. Since tephra changes reflect phases of increased volcanic input, rather than changes in background pelagic sedimentation, they were not used for stratigraphic subdivision. Instead, the lower boundary of the unit was based on paleontological data supporting transition to Upper Cretaceous microfossil assemblages in the underlying units.

Unit II is an ~23.82 m thick (46.90–70.72 mbsf) Upper Cretaceous (Maastrichtian) succession of slightly to heavily burrowed pinkish-brown to pale brown clayey-nannofossil ooze to chalk with minor interbeds of brown to gray ash to tuff, both of which are commonly altered. The Cretaceous/Paleogene (K/Pg) boundary that is assumed to form the boundary between Units I and II was not recovered. Unit II differs from Unit I in that clay content (i.e., brown color) remains high throughout. In addition, Unit II lacks black ferromanganese layers seen in the lower Unit I, and it records the first appearance of inoceramid shell fragments downhole. The pelagic sediment of Unit II is characterized by cyclical changes in color at a 10–60 cm scale, which most likely correspond to fluctuation in the relative abundance of clays and Fe oxides relative to carbonates. At least 20 layers of typically well-defined, brown to dark brown graded and/or bioturbated tephra occur throughout. The lower boundary of Unit II is taken as the base of the lowermost graded tephra layer, below which both biostratigraphic and paleomagnetic data suggest a stratigraphic gap or period of reduced sedimentation of ~3 My.

Unit III represents more than half (84.08 m) of the sedimentary cover (70.72–154.80 mbsf). It is a Campanian to possibly latest Santonian succession of bioturbated clayey-nannofossil chalk with intermittent, commonly burrowed graded tephra interbeds. Overall, Unit III represents a long duration of seafloor pelagic sedimentation, interspersed with tephra input of differing types. Changes in color at a 10–60 cm scale, similar to those observed in Unit II, are still locally recognized in Unit III, but these are more commonly obscured by irregular occurrences of slightly to extensively bioturbated tephra layers. Unit III is further subdivided into three subunits (Subunits IIIA, IIIB, and IIIC) based on color variation (pinkish to green) that reflects clear variations in the overall preserved oxidation state in the chalk and also attendant changes in the abundance and type of tephra deposits. Subunit IIIA is a 22 m thick succession (70.72–92.23 mbsf) dominated by pinkish-brown chalk with minor gray tephra layers typically <5 cm thick. Subunit IIIB is an ~41 m thick succession (92.23–133.53 mbsf) dominated by greenish-gray chalk with slightly more abundant black tephra layers (~5–15 cm thick). Finally, Subunit IIIB is a 21 m thick succession (133.53–154.80 mbsf) dominated by pinkish-brown chalk with fewer intervals of gray, brown, and black tephra layers (also ~5–15 cm thick). Rare <15 cm thick layers of hyaloclastite appear toward the base of the unit closer to the contact with underlying volcanic basement. This contact is marked by the top of a massive lava overlain by a 0.5 cm thick layer of altered hyaloclastite and bioturbated clayey-nannofossil chalk. As previously observed in the sedimentary cover at Site U1576, Unit III at Site U1577 preserves a detailed record of changes in paleoenvironment at Valdivia Bank (e.g., cyclical patterns and possible anoxic versus oxic seafloor conditions, or depositional diagenesis) for the Campanian and Maastrichtian.

Igneous Petrology and Volcanology

Hole U1577A penetrated 39.1 m of igneous basement with 28.0 m of igneous rocks recovered (80% recovery), representing Lithostratigraphic Unit IV in the overall subseafloor succession. Hole U1577A terminates within a massive basalt flow indicating a minimum thickness of 19.07 m. Igneous basement was intersected from Section U1577A-18R-1 through 26R-1. The volcanic succession consists of a single unit (Igneous Lithologic Unit 1) made up of highly phyric basalt that is subdivided into three subunits (i.e., massive flows) based on features that identify flow boundaries. All subunits are porphyritic, though the groundmass texture grades to aphanitic adjacent to flow boundaries. The uppermost subunit contains a glassy rim in contact with the overlying pelagic sediment. The massive flows contain ~18% phenocrysts, with ~15% plagioclase, 2%–5% pyroxene, and 0%–3% olivine. The lavas are sparsely vesicular and contain round vesicles 1–2 mm in diameter, filled with at least one secondary mineral (e.g., clay, calcite, and/or zeolite). Groundmass in flow interiors consists of fine- to medium-grained clinopyroxene and plagioclase in subophitic textures, often showing late-stage crystallization after olivine and plagioclase. In flow interiors, the groundmass has a seriate texture and coarse crystal size distribution, which approaches that of the phenocrysts. Mesostasis (quenched melt) forms irregular globules that consist of microcrystalline plagioclase, clinopyroxene, and Fe-Ti oxides. The flow margins consist of plagioclase-clinopyroxene-olivine phyric basalt. Plagioclase is still the dominant phenocryst phase in the form of similarly blocky or tabular glomerocrysts (up to 2.4 mm in size) but with much lower abundance than in flow interiors (~5%). Olivine (altered to saponite) and clinopyroxene are less common and form small anhedral grains (up to 0.6 mm). The groundmass in samples from flow margins is markedly distinct from flow interiors: plagioclase, clinopyroxene, and Fe-Ti oxides are very fine grained, showing intergranular textures. Plagioclase forms small needlelike skeletal crystals (<0.4 mm), while clinopyroxene (<0.08 mm) forms small blocky crystals. There is no seriate gradation in size, as seen in the flow interiors. Mesostasis forms distinct regions with microcrystalline textures. Secondary minerals are relatively scarce, but those that do occur are disseminated as limited peripheral alteration or oxidative films around crystals, and these changes impart minor color variations from the unaltered blue-gray flow interiors to a light brown hue. Oxidative changes also occur as discolored haloes extending 2–4 cm away from calcite- and Fe oxyhydroxide-filled fractures and veins.

Biostratigraphy

Calcareous nannofossil and planktonic foraminifera biostratigraphy was performed on core catcher (CC) sections from Hole U1577A. Nannofossil analysis included 15 CC samples and two toothpick samples, and foraminifera analysis included seven CC samples. Foraminifera sample processing was difficult, limiting the number of samples analyzed in the time available for this hole. Planktonic foraminifera and calcareous nannofossil ages show good agreement throughout the hole.

Notably, Section U1577A-1R-CC recovered sediments that were late Paleocene (Thanetian stage) in age referring to ~58.0 Ma. Therefore, the shallowest possible sample (i.e., the mudline) was examined to determine whether this age also corresponded to the top of the sequence, or if a thin layer of younger sediment was present. Investigation of the mudline revealed sediments with a maximum age of latest Pleistocene, indicating present-day sedimentation is not below the carbonate compensation depth. This likely indicates a long persistent erosional surface at this site; thus, a major unconformity exists between sediments less than ~0.43 Ma and the latest Paleocene-aged sediments recovered in Core 1R. Additional samples from Core 1R will be analyzed postexpedition to identify the precise location of this unconformity. A nearly continuous succession of late Paleocene (Thanetian) to Late Cretaceous (Campanian) sediment was recovered from Sections 1R-CC to 17R-CC. An apparent unconformity was discovered between Sections 7R-CC and 8R-CC spanning the Maastrichtian/Campanian boundary, encompassing a time gap of about 5.6 Ma between ~69.0 and 74.6 Ma. This observation is corroborated by NGR data measured on whole-round core sections and magnetostratigraphic data. Higher resolution sampling through Core 8R is required to identify the true range of missing time due to this unconformity.

The age of the oldest sediment in Hole U1577A is unclear. Foraminifera and calcareous nannofossils do not record Santonian stage (Upper Cretaceous) marker taxa. However, paleomagnetic data indicate that the interval of the Cretaceous Normal Superchron was intersected (possibly in Section 17R-3), considered to be the boundary between the Campanian and Santonian stages of the Upper Cretaceous. In Section 17R-CC, foraminifera and nannofossils agree on an early Campanian age from ~79.00 to 81.38 Ma. However, the poor preservation of planktonic foraminifera limited the complete evaluation of the assemblage. A toothpick sample was taken from just above the sediment-basement contact, but confident Santonian markers were not observed. Last occurrences of foraminifera markers *Dicarinella asymetrica*, *Dicarinella concavata*, and *Sigalia deflaensis* coincide with the Santonian/Campanian boundary (83.64 Ma) (Gradstein et al., 2012).

Paleomagnetism

Sedimentary Cores U1577A-1R through 18R are mostly made up of partially to fully consolidated clay and chalk. Archive half sections 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^{-3} to 10^{-1} A/m. Most sediments have median destructive fields ranging from 10 to 30 mT. Thermal demagnetization spectra of sediment specimens often revealed slow unblocking of magnetization in the 200°–400°C range, with a sharper drop in magnetic moment close to 580°C (the Curie temperature of magnetite). This demagnetization behavior suggests that the dominant magnetization carriers in sediments from Hole U1577A are likely a mixture of titanomagnetite with varying Ti concentrations and magnetite. A total of eight polarity chrons (C) were identified in these sections that cover the Thanetian (late Paleocene; C26n in Core 1R) to the early Santonian (Late Cretaceous; C34n near the contact with basement). There are three major breaks in the magnetostratigraphy, probably due to poor core recovery or unconformities: (1) between Cores 4R and 5R, where sediment ages jump from C26r to C28n; (2) between Cores 5R and 6R, where sediment ages jump from C28n to C30n; and (3) in Section 8R-3, where sediment ages jump from C31r to C33r. All of these gaps are consistent with the available biostratigraphic markers for these cores.

Igneous rocks recovered from Site U1577 spanned Cores 18R through 26R. The igneous rocks had NRM values ranging from slightly below 1 A/m to slightly above 10 A/m. Nearly all igneous cores displayed a positive polarity magnetization after AF cleaning to 20 mT, which is compatible with the polarity chron assignment of C34n (Cretaceous Normal Superchron) observed in the sediments above the sediment-basalt contact. Occasionally, basalts from sections with large hydrothermal veins exhibited reversed polarity, which likely reflects secondary remagnetization due to alteration. Most of the igneous rocks had median destructive field values between 5 and 25 mT and exhibited a range of thermal demagnetization behaviors. Some igneous specimens exhibited lower maximum unblocking temperatures around 200°C while others showed higher unblocking temperatures near the magnetite Curie temperature of 580°C. The remainder of specimens progressively lost their magnetization between 100° and 350°C. This wide range of thermal demagnetization behaviors implies the coexistence of several magnetic phases including pseudosingle domain to multidomain magnetite and titanomagnetite with a large range of Ti concentrations.

Geochemistry

At Site U1577, 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 except for low alkalinity and high pH anomalies observed within Lithostratigraphic

Subunit IIIB. Across the entire sedimentary succession, overall nonlinear increases of calcium and decreases in magnesium were observed. Two maxima of IW silicon were found at the top and bottom of the sediment succession, similar to Site U1576. A broad IW manganese peak was observed from Lithostratigraphic Subunits IIIB and IIIC, corresponding to a slight decrease of sulfate concentration. Compared to previous sites, IW ammonium and phosphate concentrations are lower by a ratio of nearly 1:1. In summary, IW geochemistry at Site U1577 indicates slower diagenesis of calcite, silica, and organic matter than at the other Valdivia Bank Sites (U1575 and U1576). Sediment samples were also analyzed for the content of $CaCO_3$, total carbon, and total organic carbon. $CaCO_3$ content declines in Unit III while organic carbon content is relatively consistent in the overall sedimentary sequence. Methane concentrations measured from the headspace gas are lower than the atmospheric background level of 2.0 µL/L.

Site U1577 recovered three igneous lithologic subunits of massive lava flows consisting of highly phyric basalt. For the determinations of major and trace elements, seven samples were analyzed by inductively coupled plasma–atomic emission spectroscopy. Additionally, 158 measurements were conducted on archive half section pieces by portable X-ray fluorescence spectrometry. The loss on ignition (LOI) represents an indicator for the degree of alteration, and the analyzed samples show a low LOI of <1.35 wt%. Overall, Site U1577 samples are extremely homogeneous, showing a limited geochemical variation downhole that is less variable in composition than the other Valdivia Bank Sites U1575 and U1576. Based on the low LOI and homogeneous composition, we conclude that the brownish discoloration of some samples reflects minor oxidation without significant element addition/subtraction. All samples from Site U1577 are classified as basalts and have a tholeiitic composition. The Ti-V composition of the basalts from Site U1577 is similar to the other Valdivia Bank sites and comparable to mid-ocean ridge basalts and ridge-centered ocean island basalts. On bivariate diagrams of Mg# versus the other major and trace elements, Site U1577 samples form tight clusters that overlap with previous dredge and Deep Sea Drilling Project drill site samples from the Walvis Ridge. Consistent with the absence of olivine, the olivine-free Subunit 1b is slightly lower in MgO, Mg#, Ni, and Cr relative to Subunits 1a and 1c.

Physical Properties

Physical properties measurements were made on whole-round cores, section halves, and discrete samples from 26 cores recovered in Hole U1577A. A suite of measurements, including NGR, magnetic susceptibility (MS), bulk density, *P*-wave velocity, porosity, and thermal conductivity record two lithostratigraphic breaks: (1) a boundary between calcareous ooze/chalk units at ~70 mbsf, and (2) the sediment-basalt contact at ~155 mbsf. The first lithostratigraphic boundary, between Lithostratigraphic Unit II and Subunit IIIA, is defined by an abrupt shift from relatively high, wide-ranging NGR values to a narrower and lower range of values (~10 to ~16 counts/s) at ~70 mbsf. At the same depth, NGR observations are correlated to paleomagnetic measurements: remanent magnetism indicates a shift from Chron C31n to C33r and suggests that part of the sedimentary record is missing. The sediment-basalt contact is clearly imaged at ~155 mbsf as an increase in MS and bulk density (up to 2709 SI × 10^{-5} and 2.95 g/cm^3, respectively) and an accompanying decrease in porosity and NGR counts (as low as 2.73 vol% and 4.98 counts/s, respectively). Sediments above the basalt contact have comparably lower MS and bulk density (up to 647 SI × 10^{-5} and 2.12 g/cm^3, respectively), and higher NGR and porosity (up to 31.3 counts/s and 73.2 vol%, respectively). Bulk density, MS, and NGR values indicate a continuous package of relatively unaltered basalt with no interbedded sediments from ~155 mbsf to the bottom of Hole U1577A at 193.4 mbsf. Physical properties measurements also record lithologic variations within the sediment interval that align with observations from previous sites. As in Holes U1576A and U1576B, higher MS values (e.g., 647 SI × 10^{-5} in Section U1577A-8R-3, at ~71 mbsf) are associated with tephra layers within the sediment interval. Additionally, sediments between ~80 and ~90 mbsf appear to display cyclic variations in NGR that are similar to cycles observed in Hole U1576A.

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.