IODP Expedition 385: Guaymas Basin Tectonics and Biosphere

Site U1546 Summary

Background and Objectives

Site U1546 (proposed Site GUAYM-02B) is located ~51 km northwest of the axial graben of the northern Guaymas Basin spreading segment. The primary objective for this site was the same as Site U1545 (proposed Site GUAYM-01B), located just 1.1 km away. Preexpedition seismic survey data at Site U1546 revealed a bright reflector at ~2.6 s two-way traveltime (TWT) that was interpreted as the contact with a sill intrusion. Disruption of the sedimentary strata above the interpreted sill (at ~2.3–2.6 s TWT) was supposed to have formed as response to the sill emplacement. This feature abruptly terminates laterally toward Site U1545, coincident with the termination of the underlying sill. This same sedimentary sequence appears undisrupted at Site U1545 to ~2.8 s TWT, where another sill was observed in the seismic data. Deeper sills were also interpreted at Site U1546, at ~2.75 and 2.85 s TWT. The shared objective of Sites U1545 and U1546 was to compare the composition, physical properties, geochemical gradients, and microbial communities at these sites. Thus, the major objective of Site U1546 was to provide a postintrusion sedimentary succession for comparison with the reference Site U1545, and this comparison will provide direct measurements of changes in response to sill intrusion.

Operations

We cored four holes at Site U1546. Hole U1546A is located at 27°37.8851′N, 111°52.7939′W in a water depth of 1586.1 m. In Hole U1546A, we used the advanced piston corer (APC), half-length APC (HLAPC), and extended core barrel (XCB) coring systems to advance from the seafloor to a final depth of 361.2 m below seafloor (mbsf) with a recovery of 365.7 m (101%). We made formation temperature measurements at several depths using the advanced piston corer temperature (APCT-3) and Sediment Temperature 2 (SET2) tools. In Hole U1546B, located at 27°37.8840′N, 111°52.7809′W in a water depth of 1585.6 m, we deployed the APC, HLAPC, and XCB coring tools. Cores penetrated from the seafloor to a final depth of 333.8 mbsf and recovered 351.2 m (105%). In Hole U1546C, located at 27°37.8724′N, 111°52.7568′W in a water depth of 1596.6 m, we first drilled without core recovery from the seafloor to 308.2 mbsf. Then, the rotary core barrel (RCB) coring system was deployed to advance from 308.2 mbsf to a final depth of 540.2 mbsf with a recovery of 139.7 m (60%). Coring was terminated when the safety monitoring for hydrocarbon gases obtained an anomalously low C_1/C_2 value. We then conducted downhole wireline logging in Hole U1546C with the triple combination (“triple combo”) and the Formation MicroScanner (FMS)-sonic logging tool strings. In Hole U1546D, located at 27°37.8943′N, 111°52.7812′W in a water depth of 1585.9 m, we deployed the APC, HLAPC, and XCB coring tools to advance from the seafloor to a final depth of 300.1 mbsf with a recovery of 314.7 m (105%). Holes U1546B and U1546D were dedicated to extensive microbial and biogeochemical sampling that required the deployment of perfluorocarbon tracers (PFTs) downhole on all cores to monitor drilling fluid (seawater) contamination. The pacing of coring in Holes U1546B and U1546D was at times adjusted to accommodate the complex microbial sampling program conducted on the core receiving platform. A total of 270.7 h, or 11.3 d, were spent at Site U1546.

Principal Results

Lithostratigraphy

Of the four holes cored at Site U1546, the most complete and deepest record of sedimentary and igneous rocks at this site is represented by the combination of results from Holes U1546A and U1546C. The sediments recovered are Middle to Upper Pleistocene, mostly laminated to homogenous, diatom ooze to diatom clay, comprising a single lithostratigraphic unit (Unit I). Subordinate lithologic components include nannofossils, silt-sized siliciclastic particles, and authigenic minerals such as pyrite and clay- to silt-sized carbonate (micrite). The latter is mainly dolomitic in composition, occurring as scattered crystals within the sediment. Carbonate also occurs as discrete concretions where concentrated and ultimately as more indurated intervals of limestone/dolomite at depth. The distribution of authigenic carbonates as well as the biogenic (opal-A) to authigenic (opal-CT, quartz) silica phase transformations produce subtle yet distinct lithologic changes supporting the subdivision of Unit I into four subunits (IA, IB, IC, and ID). The transitions between the subunits are generally gradual, occurring over more than per ~10 m, and can be difficult to define in low-recovery or heavily sampled zones. The clay-rich diatom ooze of Subunit IA becomes more micritic in Subunit IB, which in turn is underlain by the less calcareous, largely micrite-free, Subunit IC. The Subunit IC/ID transition is marked by diatom (opal-A) dissolution, the appearance of opal-CT, and ultimately authigenic quartz that heralds the formation of siliceous claystone in Subunit ID. Although the subunit divisions are similar to those at Site U1545, Subunit IB is thicker and shallower at Site U1546. There are also distinct zones of altered sediment above and below the Subunit ID thick basaltic to doleritic igneous body that was fully penetrated in Hole U1546C and interpreted as a hypabyssal sill. The mixed biogenic and siliciclastic sediments along with their characteristic lamination are consistent with a Middle to Upper Pleistocene, hemipelagic and suboxic to anoxic depositional environment.

Igneous Petrology and Alteration

Mafic sill material was encountered in Holes U1546A and U1546C at depths of 354.6 and 348.2 mbsf, respectively. In Hole U1546A, the sill was penetrated over an interval of 6.0 m, whereas Hole U1546C cored through the bottom sill/sediment contact, resulting in a total sill thickness of 83.5 m based on core recovery and ~74 m based on downhole logging data. The sill is made up of highly altered basaltic rock at the top followed by doleritic and gabbroic intervals.

A doleritic texture resumes again below the gabbroic interval, followed by a short basaltic interval at the bottom contact. The top and bottom basaltic intervals show chilled margin contacts with the adjacent sediments. The basalts are highly vesicular and altered, with rounded to subrounded calcite amygdules. The cryptocrystalline groundmass hosts plagioclase phenocrysts. The doleritic intervals close to the basaltic layers are sparsely vesicular and gradually turn into nonvesicular doleritic rock in deeper cores. A ~12 m thick gabbroic interval is intercalated between the doleritic layers. The gabbroic and doleritic lithologies show both sharp and gradational contacts during the transition. Plagioclase phenocrysts are present throughout the doleritic intervals, while pyroxene pseudomorphs occur as a minor phenocryst phase in the bottom doleritic layer, below the gabbroic interval. No pyroxene phenocrysts were observed in the upper doleritic layer.

Structural Geology

A few intervals of tilted beds were seen within the sedimentary section of Lithostratigraphic Unit I. Hole U1546A showed tilted bedding in the uppermost two Subunits IA and IB, from 98 to 117 mbsf. Hole U1546B revealed tilted bedding in Subunit IB, from 115 to 124 mbsf. Hole U1546D had tilted bedding in Subunit IB from 112 to 120 mbsf and from 145 to 156 mbsf. Brittle fractures and faults were found in sedimentary cores below 200 mbsf in Hole U1546D, and below 166 mbsf in Hole U1546B. These had intermediate apparent dips (30°–60°). Where displacements could be measured, they were ≤5 cm. Six vertical veins were measured in sedimentary rocks at 433 mbsf in Hole U1546C. Within the recovered igneous rocks, fractures and veins were measured for true dip from whole-round (WR) cores before they were split. A total of 49 such structures were identified in Hole U1546C. No veins were seen in the igneous rocks at the bottom of Hole U1546A.

Biostratigraphy

At Site U1546, preservation of calcareous nannofossils is good/moderate to poor throughout the entire sedimentary sequence. In general, nannofossils are abundant and well preserved in the upper ~100 m of the sequence. Below ~100 mbsf, there is an alternation between intervals with barren/few or common/abundant nannofossils. Preservation is good/moderate in samples with common/abundant nannofossils and poor in those with few/rare abundances. In general, marine diatoms were dominant/abundant with good/moderate preservation down to ~312 mbsf, and barren to the bottom of Holes U1546A and U1546C. The bottom (first appearance datum) of the calcareous nannofossil *Emiliania huxleyi* dates the upper part of the sediment sequence to Holocene–Middle Pleistocene (0–0.29 Ma; 0–249.28 mbsf in Hole U1546A). In contrast, the absence of calcareous nannofossil *Pseudoemiliania lacunosa* and marine diatom *Fragilariopsis reinholdii* in the underlying interval indicates a Middle Pleistocene age (0.29–0.44 Ma) for the lower part of Hole U1546A. *P. lacunosa* was observed in the basal core catcher sample from Hole U1546C (539.84 mbsf), suggesting an age older than the top (last appearance datum) of *P.*

lacunosa at 0.44 Ma. The estimated average sedimentation rate is 1020 m/My (102 cm/ky) at this site.

Paleomagnetism

We conducted alternating field (AF) demagnetization with the superconducting rock magnetometer (SRM) on archive-half sections up to 20 mT on all cores from Holes U1546A and U1546C. The drilling-induced overprint was successfully removed on all APC and HLAPC cores (from the seafloor to ~270 mbsf) upon demagnetization. Inclination values after demagnetization at 20 mT cluster around 43°, which is slightly lower than the expected geocentric axial dipole (GAD) inclination at the latitude of the site. A detailed analysis of the remanence of discrete samples from Hole U1546A showed that the drilling-induced overprint is removed by 10 mT and the characteristic remanent magnetization is in agreement with the SRM measurements. Unfortunately, the XCB and RCB cores were irreversibly overprinted. Natural remanent magnetization (NRM) of archive-half sections decreases at ~80–100 mbsf (Hole U1546A), in a depth interval that corresponds to the sulfate/methane transition zone (SMTZ). The magnetic mineral assemblage becomes coarser and low-coercivity minerals, such as (titano-)magnetite, are dominant. The AF demagnetization protocol was not appropriate for the igneous rock sections of Hole U1546C. We thus focused on thermal demagnetization of discrete samples. Two groups of samples distributed in the sill intrusion were identified: a first group in the upper 18 m of the sill contain fine-grained magnetite, and a second group is dominated by coarse-grained titanomagnetite in the lower 57 m. Anisotropy of magnetic susceptibility shows a mixture of prolate and oblate behavior above the sill and a dominant prolate behavior below it. We assigned all cores in Holes U1546A and U1546C to the normal Brunhes Chron C1n (<0.78 Ma). No paleomagnetic measurements were conducted in Holes U1546B and U1546D.

Inorganic Geochemistry

A total of 94 interstitial water (IW) samples were collected at Site U1546 (Holes U1546A, U1546B, U1546C, and U1546D). Based on the sulfate profile, the SMTZ is estimated to be at ~110 mbsf. Around this depth, sulfide, alkalinity, and phosphate reach their maximum values, and barium concentration starts to increase. However, the depth of maximum concentrations of alkalinity and phosphate is slightly offset from the SMTZ. Ammonium gradually increases downhole until the sill is reached. Biogeochemical processes observed from the seafloor to 120 mbsf are mainly related to anaerobic degradation of organic matter and sulfate-dependent anaerobic oxidation of methane. Just above and below the sill, a number of significant excursions (increasing or decreasing) were observed for many IW dissolved elements (such as K^+, B, Mg^{2+}, Sr^{2+}, Li^+, Ba^{2+}), which could be related to changes in mineralogy or other factors related to the sill intrusion. Between the SMTZ and the sill intrusion, the IW chemical properties are likely to be influenced by combined biogeochemical processes and sediment/water interaction associated with the sill intrusion as well as precipitation/dissolution processes, including opal-A dissolution, authigenic carbonate precipitation, and dolomite formation.

Organic Geochemistry

At Site U1546, we sampled and analyzed gas and solid-phase samples. In Holes U1546A to U1546D, one headspace gas sample was analyzed per 9.5 m advance for routine hydrocarbon safety monitoring. The carbon, nitrogen, and sulfur contents of particulate sediment were characterized, and source rock analysis was performed on selected solid-phase samples. For the sediments recovered in Holes U1546B and U1546C, both headspace and void gas were analyzed for their hydrocarbon contents, the amount of void space was quantified, H_2 and CO contents were measured, and the carbon, nitrogen, and sulfur contents of sediment were characterized. During igneous rock recovery in Hole U1546C, WR core pieces of rock were incubated in sealed trilaminated foil barrier bags to examine degassing of hydrocarbons. In general, methane increases with depth in each hole with 1–2 local maxima. C_2–C_6 hydrocarbons are detectable at depths below ~90 mbsf, and all increase with depth. In Hole U1546C, the low C_1/C_2 values necessitated the termination of coring. From elemental and source rock analysis we infer that the primary source of organic matter is marine in origin, and the thermal maturity of organic matter varies based on the proximity of the sill. In Holes U1546B and U1546C, H_2 and CO are present in nM concentrations.

Microbiology

Sediment cores for microbiological studies were obtained from APC, HLAPC, and XCB cores in Holes U1546B and U1546D. After drilling to 308 mbsf without core recovery, Hole U1546C was also sampled along its deeper, hydrothermally heated sediment column above, within, and below the penetrated sill. These Hole U1546C samples represent important horizons that will further our understanding of the impact sill emplacement has on geochemistry and extant microbial communities within the hyperthermophilic zone. Syringe samples for cell counts, 3D structural imaging, and RNA analyses were taken on the catwalk, fixed or frozen, and stored for further analyses. WR core samples were either stored in a −80°C freezer or temporarily stored in a cold room (~8°C) and then processed for shore-based analyses. WR core sample processing was conducted either inside a Coy Laboratory Products anaerobic chamber or on the bench with a KOACH open clean zone system to maintain highly sterile conditions. Samples for PFT measurements were taken on the core receiving platform by syringe at 17 horizons. Cell abundance for selected samples was determined by direct counting with an epifluorescence microscope. Cell abundance in seafloor sediment was roughly 1000× higher than the bottom seawater and gradually decreased downhole. At deeper intervals, cell abundance dropped below the detection limit of the protocol that we used for the shipboard cell counting program.

Physical Properties

Physical properties of the recovered cores and host formation were measured on WR and working-half sections and through downhole wireline logging, respectively. Measurements on WR and working-half sections were compared between Holes U1546A, U1546B, U1546C, and U1546D, and with downhole measurements obtained from Hole U1546C for lithostratigraphic characterization and correlation between core description, logging data, and preexpedition seismic survey profiles. Our analysis identified the same two large-scale major petrophysical variations as found at Site U1545, with a transition at ~280 mbsf. All Site U1546 physical properties at ~355–430 mbsf highlight the presence of the ~74 m thick sill. Twelve in situ formation temperature measurements were conducted using the APCT-3 and SET2 tools. Extrapolated temperature values range from 10.05°C at 32.3 mbsf to 67.18°C at 323 mbsf. These values, together with the seafloor temperature of 3.96°C, indicate that temperatures increase with depth along a linear geothermal gradient of 219°C/km. The slope of the linear fit between thermal resistance and formation temperature indicates a heat flow of 233 mW/m^2. Thermal conductivity varies between ~0.66 and ~1.00 W/(m·K) within the first ~345 mbsf, which marks the upper sill/sediment contact. Sixteen hard rock thermal conductivity measurements were made on sill samples from ~348 to ~432 mbsf, yielding a mean thermal conductivity of 1.72 ± 0.14 W/(m·K). Downhole logging caliper measurements through the sill show borehole diameter values close to the bit size, consistent with the formation strength of the sill. The sill/sediment transitions can be clearly identified at ~356 mbsf for the top contact and at ~430 mbsf for the bottom contact. Bulk density for sediments generally ranges from ~1.2 to ~1.5 g/cm^3 and shows variations in trends at ~270 and ~310 mbsf. The average density of the sill is 2.8 g/cm^3. Porosity shows a linear decrease from 90% at the seafloor down to 73%–82% at ~309 mbsf. A significant decrease in sediment porosity can be observed at the top and bottom contacts with the sill. Porosity inside the sill is relatively low (~3%) except for 12% in the upper part of the sill. Compressive strength increases by 1.1 kPa/m and shear strength increases by a value of 0.6 kPa/m. Natural gamma radiation (NGR) values exhibit an increase from ~10 to 25 counts/s down to 270 mbsf. NGR values inside the sill are very low compared to the host sediments, between 2 and 5.2 counts/s. Downhole NGR measurements inside the sill are consistent with WR core laboratory measurements. Resistivity measurements show large relative variations of 0.4 to ~200 Ωm that typically correlate with variations in density and porosity. Core-based magnetic susceptibility (MS) values are mainly constant to a depth of ~355 mbsf. MS increases considerably at the sill/sediment transition. The same applies to measured *P*-wave velocities. At the sill/sediment transition, *P*-wave velocities show intermediate values between the sill (~5 km/s) and surrounding sediments (~1.6 km/s).