IODP Expedition 375: Hikurangi Subduction Margin

Site U1520 Summary

Background and Objectives

The primary objective at Site U1520 was to sample the sedimentary sequence on the subducting Pacific plate to provide insight into the lithologies and conditions expected deeper along the subduction interface and within the slow slip event (SSE) source area. The site lies approximately 95 km from shore and 16 km east of the deformation front, in ~3520 m water depth. Site U1520 was expected to encounter sediments and rocks of late Quaternary to Cretaceous age, based on regional seismic stratigraphic interpretation of stratigraphy of the Hikurangi Plateau and Hikurangi Trough. Beneath the seafloor, a succession of clastic trench turbidites and related sediments overlie the older pelagic sedimentary and volcanic sequence of the subducting Hikurangi Plateau. The upper ~610–640 m of the section was expected to consist mainly of mud and sand turbidites, hemipelagic sediment, debris flow material, and minor ash, of predominantly Pliocene–Quaternary age. The package from ~640 to ~840 m below seafloor (mbsf) was expected to comprise Late Cretaceous, Paleogene, and Miocene sedimentary rocks of the Hikurangi Plateau cover sequence, including nannofossil chalk, mudstone, tephra, and sandstone, with possible unconformities. The strongly reflective sequence below 840 mbsf was interpreted to include basalts, volcaniclastic sediments, and breccia, with intervals of pelagic chert and/or limestone.

The objective of coring at Site U1520 was to sample the entire sedimentary section on the Pacific Plate, with a highest priority on recovering the materials below ~600 mbsf that represent the protolith for material transported into the deeper SSE source region. In order to maximize the likelihood of successfully coring the deep portion of the section, we drilled in casing to 642 mbsf at Hole U1520C, and undertook rotary core barrel (RCB) coring below the casing, to 1054.1 mbsf. Following coring at U1520C, we conducted wireline logging in the open hole below casing, logging from 642–947 mbsf. We returned to Site U1520 later in the Expedition to undertake advanced piston corer/extended core barrel (APC/XCB) coring at Hole U1520D to sample the upper 642 m of the sedimentary section.

The scientific objectives of coring at U1520 were to define any structures and deformation, physical properties, lithology and composition, and interstitial fluid geochemistry of the incoming material in its “presubduction” state. Coring data will also be used for core-log-seismic integration across the Hikurangi Trough. Priorities for postexpedition analysis of cores include measurements of the mechanical, elastic, frictional, and hydrological properties of the incoming sediment and basement, along with detailed analyses of composition and alteration.

Operations

Hole U1520C

We first occupied Site U1520 while waiting for the R/V *Tangaroa* to deliver replacement seals needed for the observatory installation at Site U1518. Upon arrival at 0257 h (UTC + 12 h) on 28 March 2018, the thrusters were lowered and the dynamic positioning system was engaged. We first fabricated the base of the reentry cone, put together the hydraulic release tool (HRT) needed to deploy the reentry system, and assembled a casing string consisting of 54 joints of 10¾ inch casing and a casing shoe, and secured it in the moonpool at 0130 h on 29 March. Next, we put together the drilling assembly needed to drill the reentry system into the seafloor. The drilling assembly was composed of a 9⅞ inch drill bit, an underreamer with its arms set to 14 inch, and a mud motor to rotate the bit and underreamer in isolation from the casing. The underreamer arms were tested and the drilling assembly was completed and landed inside the casing at 0500 h on 29 March. The drilling assembly and HRT were connected to the casing and mud skirt, the reentry cone was assembled in the moonpool, and the reentry system was lowered to the seafloor. While the reentry system was being lowered to the seafloor, the R/V *Tangaroa* arrived at 1615 h on 29 March to deliver the replacement seals needed for the CORK-II installation at Site U1518.

The subsea camera was deployed to monitor the reentry cone and base while drilling it into the seafloor. Hole U1520C (38°58.1532′S, 179°7.9112′E, 3522.1 m below sea level [mbsl]) was started at 1940 h on 29 March and it took ~27 h for the bit to reach a total depth of 646 m, with the casing shoe at 642 m. Once the drilling system was released from the reentry system, we recovered the subsea camera and then the drill string at 1120 h on 31 March. With the reentry system completed, we departed for Site U1518 at 1310 h on 31 March to complete the observatory installation there.

We returned to Site U1520 on 2 April, following a ~10 h deviation to the Gisborne Pilot Station for a personnel transfer. We arrived at Hole U1520C at 1848 h on 2 April. We assembled an RCB coring assembly and reentered Hole U1520C at 0525 h on 3 April. The next several hours were spent cleaning cuttings out of the inside of the 642 m deep casing. RCB coring started at 1200 h on 3 April. Cores U1520C-2R to 44R penetrated from 646.0 to 1054.1 m and recovered 235.81 m (58%). Nonmagnetic core barrels were used for all cores. Coring was terminated so that Hole U1520C could be logged before the weather deteriorated.

To prepare the hole for logging, we circulated the cuttings out of the hole with mud and recovered the RCB bottom-hole assembly (BHA). The subsea camera was deployed to check the reentry cone, which seemed to have sediment inside, and the cone was flushed with seawater. Once the drill string was recovered, we made up a logging BHA and lowered it to the seafloor. Hole U1520C was reentered at 0250 h on 9 April and the drill pipe was set at 599 m for logging, 42 m above the casing shoe. We deployed a modified triple combo tool string with the following tools from the bottom up: Dipole Sonic Imager (DSI; sonic velocity), High-Resolution Laterolog

Array (HRLA; resistivity), Hostile Environment Litho-Density Sonde (HLDS; caliper only, without the density source), and Enhanced Digital Telemetry Cartridge (EDTC; gamma ray and telemetry). We made two logging passes from 642 to 947 mbsf, where we encountered an obstruction at 107 m from the bottom of the hole. The tools were back on the rig floor at 1505 h on 9 April, and the drill string was recovered at 0010 h on 10 April, ending operations at Hole U1520C. The next objective for the expedition was to install an observatory at Site U1519 and core at Site U1526.

Hole U1520D

Our objective at Hole U1520D was to core the uppermost sediments (above 646 mbsf) that we drilled without coring at Hole U1520C. After a ~6 h transit from Site U1526, we arrived back at Site U1520 at 2305 h on 24 April. After assembling an APC/XCB BHA, Hole U1520D (38°58.1475′S, 179°7.8991′E, 3520.3 mbsl) was started at 0850 h on 25 April. Cores U1520D-1H to 67X advanced from 0 to 642.3 m and recovered 553.78 m (62%). Within this interval, we drilled without coring from 189.3 to 220.0 m and from 270.8 to 366.6 m. Coring was suspended from 1600 h on 29 April until 1315 h on 30 April while we waited on the weather. Nonmagnetic core barrels were used with all APC cores. Formation temperature measurements were taken with the advanced piston corer temperature tool (APCT-3) for Cores 4H, 7H, 10H, 13H, 16H, 19F, 23F, and 27F.

Principal Results

Lithostratigraphy

Six lithostratigraphic units were defined based on cores recovered from Holes U1520C and U1520D. The sediments and sedimentary rocks range in age from late Early Cretaceous to Holocene. Thin tephra layers are scattered throughout most of the succession. Lithologic Unit I begins at the seafloor and extends to 110.5 mbsf. This interval consists of greenish gray hemipelagic mud punctuated by graded beds of dark gray silt and sand. We interpret the coarser beds to be products of deposition by turbidity currents on the floor of the Hikurangi Trough.

Unit II (110.5–222.0 mbsf) consists of hemipelagic mud with silt interbeds. These turbidites are generally finer grained and thinner than those recovered in Unit I. Based on interpretations of seismic reflection data, Unit II represents the distal edges of the Ruatoria debris avalanche, as interpreted from seismic reflection images. Mesoscopic evidence is lacking, however, for the types of soft-sediment gravity-driven deformation expected within a submarine slide or debris flow deposit (e.g., truncated and rotated laminae, irregular bedding dips, fragmentation of cohesive mud clasts, clasts-in-matrix fabrics, and flow banding).

Unit III (222.0–509.82 mbsf) is similar to Unit I, but without thick beds of sand. The turbidites are characterized by graded beds of fine sand to silt with planar laminae and cross-laminae. We interpret the depositional environment to be within the Hikurangi Trough during a period of time in which turbidity currents were less frequent, more dilute, and finer in grain size.

Unit IV begins at 509.82 mbsf in Hole U1520D and extends to 848.45 mbsf in Hole U1520C. Lithologies change markedly across the unit boundary to a Miocene–Paleocene pelagic carbonate facies that includes light greenish-gray marl, light brownish-gray calcareous mudstone, and pale brown chalk. Secondary lithologies include matrix-supported gravity-flow deposits and volcanic tuff. The debris flow deposits display contorted to fragmented marl and chalk, together with angular to subrounded clasts of volcaniclastic sandstone and vesicular basalt.

Unit V (848.45–1016.24 mbsf) is dominated by granule-size volcaniclastic conglomerate. These Cretaceous deposits are characterized by subangular clasts of basalt that range in size from a few millimeters to 6 cm. The fabric ranges from clay-matrix supported to clast supported, and the mechanisms of emplacement probably included grain flow and debris flow. Alteration of the basalt clasts to palagonite and clay minerals is pervasive. Zeolites and calcite are common cements.

Unit VI (1016.24–1045.75 mbsf) comprises a blend of rock types whose stratigraphic organization and thicknesses are not resolvable. Much of the unit contains alternating volcaniclastic conglomerate and mudstone with a distinctive dark bluish-gray to greenish-gray color. Additional lithologies include pyrite-rich siltstone, organic-rich black mudstone, white limestone, reddish-brown siltstone, and vesicular basalt with amygdules.

Biostratigraphy

The sedimentary sequence and upper portion of the Hikurangi Plateau basement cored at Site U1520 represent a discontinuous Holocene to late Cretaceous succession comprising several hiatus-bounded sedimentary packages.

Planktonic foraminifers and calcareous nannofossils indicate that Holes U1520D and U1520C recovered Holocene aged sediments (<0.009 Ma) from 0–5.93 mbsf; Pleistocene (0.009–2.17 Ma) from 15.40–537.21 mbsf; Pliocene from 543.45–577.35 mbsf; a Pliocene/Miocene boundary sequence from 598.06–587.74 mbsf; Miocene from 635.65–746.89 mbsf; late Oligocene from 756.62–766.20 mbsf; middle to early Eocene from 775.17–825.53 mbsf; and middle to early Paleocene from 827.04–848.01 mbsf. The underlying volcaniclastic sequence (849.96–1045.75 mbsf) comprising lithological Units V and VI is largely unfossiliferous, except for the 950.22–953.45 mbsf and 1016.69–1017.82 mbsf intervals, where Late Cretaceous foraminifers were recovered. Organic-rich sediments from 1036.57–1037.21 mbsf also included poorly preserved radiolarian faunas and siliceous branching tube-like fossils of unknown affinity. Minor reworking of planktonic foraminifers was evident throughout the cored sedimentary succession but was most notable at ~512 mbsf, where common, very well preserved middle to early Eocene, Miocene, and Pliocene taxa occur in a Pleistocene fauna; and at ~588 mbsf, where late Miocene (8.96–9.63 Ma) taxa dominate a Miocene/Pliocene boundary fauna.

Paleomagnetism

Paleomagnetic investigations included the measurement of the natural remanent magnetization (NRM) of archive-half sections prior to and following stepwise alternating field (AF) demagnetization to peak fields of 30 or 40 mT. In addition, 1–2 discrete samples per core were subjected to more detailed AF or thermal demagnetization. The data quality and processing strategy differed somewhat for Holes U1520C to U1520D as a result of the different coring systems used, core disturbance, and recovery. With few exceptions, characteristic remanent magnetization directions calculated from data sets based on discrete samples were mostly coherent. A magnetostratigraphy was produced with confidence for cores recovered using APC and RCB drilling (0–248 mbsf and 646–850 mbsf) and tentatively for XCB cores (248–636 mbsf). The volcaniclastic deposits of Units V and VI all yield steep negative inclinations, suggesting the possibility that the entire unit may have been remagnetized. There are 18 tie-points with foraminifer (Hole U1520D) and nannofossil (Hole U1520C) data that will be used to match to the magnetic polarity timescale postexpedition.

Structural Geology

The rocks encountered at Site U1520 are generally undeformed. Bedding dips gently (<30°) over the entire depth of the hole, with the exception of folded strata within debris flow deposits. The resistivity-at-the-bit (RAB) image log shows some intervals of steeper dips that are not recognized in the cores. Discrete small displacement deformation features were observed throughout Hole U1520C (646–1036 mbsf), but are largely absent above 596.4 mbsf in Hole U1520D.

Distinct structural domains are mostly correlated with lithostratigraphic units. Domain 1 is defined by subhorizontal to gently dipping beds with no discrete deformation features, from the seafloor to 596.4 mbsf. Below this, faults (normal when sense of slip was determined) and dissolution features are present throughout Domain 2 (596.4–848.45 mbsf), which consists of the calcareous clay-rich sediments. Veins are more common in the volcaniclastic units that comprise Domain 3 (848.45–1016.24 mbsf). Finally, Domain 4 (1016.24–1045.75 mbsf) near the bottom of the hole coincides with lithostratigraphic unit VI, where deformation is dominated by minor faults.

Geochemistry

A total of 89 whole-round (WR) samples were collected and squeezed for shipboard and shore-based pore water chemical analyses. Despite the high bulk density and cemented nature of the sediments recovered in Hole U1520C, pore water was recovered in all three lithologic units. The geochemical profiles at Site U1520 are complex and reflect the combined effects of organic matter diagenesis, non-steady state sedimentation, volcanic ash/silicate mineral diagenesis, carbonate mineral diagenesis, solute diffusion, and potential lateral fluid flow within the volcaniclastic sediments of Lithostratigraphic Unit V.

Contemporary carbonate mineral recrystallization is manifested by elevated dissolved Sr concentrations within Unit IV above 769 mbsf; below this, Sr concentrations decrease monotonically to near constant values in Unit V. The decrease in Sr concentrations at the base of Unit IV suggests that carbonate recrystallization is minor, and that present-day carbonate diagenesis is restricted to the top of Unit IV. Sulfate concentrations increase linearly through the lower part of Unit IV, and remain elevated and nearly constant within Unit V. A similar pattern is observed in Sr and Mg profiles. To maintain this gradient likely requires lateral flow of a sulfate-enriched fluid in the volcaniclastic sediments.

Chloride concentrations increase linearly to a peak at 51.3 mbsf. Below this depth, Cl concentrations decrease to 142 mbsf and remain relatively constant to the base of Unit III. Collectively, these profiles suggest a zone of localized volcanic ash alteration/silicate mineral diagenesis and the precipitation of hydrous aluminosilicate minerals. Below this, within the lower portion of Unit IV and within Unit V, Cl concentrations are depleted relative to seawater and marked by several excursions to lower values over only ten to a few tens of meters, which may reflect local addition of fresh water from dehydration reactions.

A total of 93 carbonate samples were taken at Hole U1520C and 108 samples at Hole U1520D. Calcium carbonate ($CaCO_3$) in lithologic Units I, II, and III varies from 2.06 to 18.4 wt%. In lithologic Units IV, V, and VI, $CaCO_3$ varies from 0.35 to 96.9 wt%, reflecting variations in lithology. The $CaCO_3$ profile mimics the depth profile of total C and inorganic C, with similar trends in all lithological Units. In the deepest part of Unit IV, $CaCO_3$ values range from 90.0 wt% at 799.0 mbsf to 91.4 wt% at 844 mbsf. This high carbonate percentage reflects the presence of pelagic carbonate. In Unit V, peaks in $CaCO_3$ content generally reflect localized calcite cementation. Organic C values are generally low (<1.19%) throughout the section.

Physical Properties

Porosity values decrease with depth from 72% at the seafloor to 28%–38% at ~800 mbsf, with some lower values of ~40% between 40 and 106 mbsf, which correspond to sand layers. Below 800 mbsf, porosity increases to 56%. Below 855 mbsf, porosity generally decreases with depth but with substantial scatter until the bottom of the hole, associated with varying degrees of cementation.

P-wave velocity values range from 1450 to 1800 m/s between the seafloor and ~90 mbsf. Between 90 and 420 mbsf, *P*-wave velocity measurements were mostly unsuccessful due to gaps between cores and liners and expansion cracks. Between 420 and ~845 mbsf, values generally increase with depth ranging from 1500 to 2700 m/s, with little scatter. Below 845 mbsf within the volcaniclastic Units V and VI, *P*-wave velocity values exhibit significant scatter, ranging from 1800 to ~5000 m/s. Undrained shear strength increases with depth from 0–10 kPa at the seafloor to 100–150 kPa at 150 mbsf and stays constant to 400 mbsf, followed by a rapid increase with depth to ~600 kPa at 500 mbsf.

Thermal conductivity values increase with depth from 1.0 W/(m·K) at the seafloor to 1.3 W/(m·K) at ~20 mbsf, and remain nearly constant to ~550 mbsf. Some higher thermal conductivity values of 1.6–1.9 W/(m·K) are observed between 23 and 87 mbsf, which correspond to sand layers. Measurements were not made between 550 and 646 mbsf because the sediments were too indurated for a needle probe and too fragile and disturbed by coring for a half-space probe. Thermal conductivity values increase from ~1.2 W/(m·K) at 648 mbsf to 1.8 W/(m·K) at 700 mbsf and then remain relatively constant to ~850 mbsf. Below 850 mbsf, thermal conductivity is nearly constant with some scatter with an average value of 1.2 W/(m·K).

Natural gamma radiation (NGR) values range from ~0 to 75 counts/s. Mean values are between 30 and 50 in all units, except lithostratigraphic Unit IV where the mean NGR value is ~20 counts/s. NGR data from cores and logging gamma ray data show consistent trends. Magnetic susceptibility (MS) values are nearly constant with depth in lithostratigraphic Units I, II, and III and range from 20×10^{-5} to 40×10^{-5} SI. In lithostratigraphic Unit IV, MS values increase with depth from 10×10^{-5} at ~510 mbsf to 100×10^{-5} at ~700 mbsf, and decrease to ~4×10^{-5} SI at 800–849 mbsf. At the top of lithostratigraphic Unit V at ~849 mbsf, MS values shift rapidly to ~100×10^{-5} SI and then gradually increase with depth to 300×10^{-5} SI at ~900 mbsf, followed by a gradual decrease with depth to 10×10^{-5} SI at ~1020 mbsf. At 1045 mbsf there is a rapid increase to ~300×10^{-5} SI.

Downhole Measurements

Five APCT-3 equilibrium temperature measurements were combined with thermal conductivity measurements and yielded a temperature gradient of 38°C/km and a heat flow of 44 mW/m^2.

Hole U1520C was logged using a modified triple combo that included borehole diameter from a Hostile Environment Litho-Density Sonde (HLDS; mechanical caliper), Enhanced Digital Telemetry Cartridge (EDTC-B; gamma ray), High-Resolution Laterolog Array (HRLA; resistivity), and Dipole Shear Sonic Imager (DSI). The nuclear source was not deployed with the HLDS. Although some differences exist, wireline logs are generally consistent with logging-while-drilling (LWD) data collected during Expedition 372. The caliper shows that the hole ranges in size from 8 inch (likely due to collapse or swelling of clays) to 17 inch. The hole is irregular with many washouts below 780 mbsf. Within the uncased portion of Hole U1520C, gamma ray values vary between ~20 and 80 API, *P*-wave velocity varies between ~1.6 and 2.9 m/s, and resistivity is relatively constant at ~2 Ωm with the exception of strong peaks between 870 and 890 mbsf. In general, gamma ray and *P*-wave velocity are inversely correlated between 640 and 848 mbsf, and positively correlated below 848 mbsf.

Core-Log-Seismic Integration

The *P*-wave velocity measurements were integrated from LWD and wireline logging to develop a velocity model to a depth of 944 mbsf. As wireline density data were not recorded on Expedition 375, density data from LWD were merged with whole-round track and discrete sample data to construct a density model. A synthetic seismic reflection trace was developed to tie the LWD, core, and seismic data. Considering the new seismic tie from this analysis, the precise boundaries of the nine seismic units defined by Expedition 372 scientists were revised, and these units were compared with LWD, wireline data, and lithologic units from Expedition 375.

Seismic Unit 1 is 106 m thick and comprises moderate- to low-amplitude, laterally continuous reflections. Cores show the sequence to comprise mud, silt, and fine-grained sandy turbidites and hemipelagic sediments of Late Pleistocene to Holocene age. Seismic Unit 2 is 119 m thick and is characterized by moderate- to low-amplitude, semicontinuous and chaotic reflections and has been interpreted from seismic and LWD data as the Ruatoria avalanche mass transport deposit (MTD). Cores were recovered at Hole U1520D only from the upper 80 m of the unit, and the base of the unit was not sampled. The lithofacies is composed mostly of horizontal thin-bedded silty turbidites, with occasional mud intraclasts and erosional bases. The sequence appears largely undisturbed. Seismic Units 3, 4, and 5 consist of variable amplitude, laterally continuous reflections that can be traced widely along and across the Hikurangi Trough. Coring reveals that these units are composed of normally graded silty turbidites with thick volcanic ash layers near the top of the unit. Biostratigraphy indicates that these are early to late Pleistocene in age.

Seismic Units 6, 7, and 8 have a more irregular geometry than the overlying units and have moderate to low-amplitude reflections, which are locally offset by small normal faults. The disrupted nature of the reflections in seismic Unit 6 could be interpreted as one or more debris flows originating from the flanks of Tūranganui Knoll. Coring reveals that these units are composed of marl and calcareous mudstone with tuff and thin MTDs overlying chalk. Biostratigraphy indicates that these units are early Paleocene to early–middle Pleistocene in age. Seismic Unit 9 consists of high-amplitude reflections that are semicontinuous to discontinuous, and corresponds to lithologic Units V and VI, which are composed predominantly of mixed volcaniclastic lithologies and thin intervals of calcareous and black mudstone. The seismic units exhibit an overall progradational geometry towards the west, building outward into the basin away from the flank of Tūranganui Knoll. Biostratigraphy indicates that seismic Unit 9 is late Early Cretaceous to Late Cretaceous in age.