IODP Expedition 375: Hikurangi Subduction Margin

Site U1519 Summary

Background and Objectives

Site U1519 is located on the upper continental slope of the Hikurangi margin, ~38 km from shore and at a water depth of ~1000 m at the landward edge of a midslope sedimentary basin. On the basis of regional stratigraphic and seismic interpretations prior to drilling, we expected to intersect 260–270 m of horizontally layered late Quaternary basin fill comprising mass transport deposits and layered sequences including probable turbidites, underlain by a Plio–Pleistocene southeast-dipping slope sequence of mass transport deposits and layered sequences ~260–270 m thick. Beneath these, we expected to intersect Miocene sedimentary rocks (equivalent to the Tolaga group exposed onshore), within seismically reflective landward-dipping strata overlain by an erosional unconformity identified in seismic reflection data at ~540 mbsf. Expedition 372 acquired logging-while-drilling data at Hole U1519A in December 2017.

The primary objective at Site U1519 was the installation of an observatory to monitor formation pressure changes (as a proxy for volumetric strain) and temperature changes throughout multiple slow slip event (SSE) cycles. Drilling at Site U1519 during Expedition 375 also included rotary core barrel (RCB) coring in discrete intervals (108–163.6, 250–288.4, and 520–640 mbsf), and advanced piston corer (APC) coring from the seafloor to 85.8 mbsf. The main objective of coring at this site was to provide information about rock physical properties, composition, and structural geology and deformation in the upper plate above the SSE source region. Advanced piston corer temperature tool (APCT-3) in situ temperature measurements in Holes U1519D and U1519E define a temperature gradient, and provide key constraints on the thermal regime of the SSE source region. Pore fluid geochemistry data provide insights into diagenetic processes and potential sources and flow pathways of fluids sampled in the hanging wall.

One key focus for postexpedition studies on core samples will be geomechanical measurements to define poroelastic and strength properties of the formation. These data will be essential for interpretation of observatory data, such as calibrating the use of pore pressure as a proxy for volumetric strain. Similarly, measurements of strength, permeability, and elastic moduli will provide important context for the interpretation of borehole failures as indicators of in situ stress magnitude, parameterization of hydrological models, and core-log-seismic integration. Measurements of thermal properties will be used in combination with observatory temperature data to define heat flow, and to interpret thermal transients in the context of heat conduction and possible advection.

Operations

Transit to Site U1519

We arrived at Site U1519 at 1810 h (UTC + 12 h) on 13 April 2018, after waiting on weather in the Bay of Plenty.

Hole U1519B Observatory

In preparation for installing the observatory, we predrilled the observatory hole. A bottom-hole assembly (BHA) with a 14¾ inch drill bit was lowered to the seafloor. Hole U1519B (38°43.6426′S, 178°36.8655′E, 1000.4 m below sea level [mbsl]) was started at 0105 h on 14 April and reached a total depth of 285.1 m. Next, a reentry cone and mud skirt were released from the moonpool and allowed to free-fall down the drill string to the seafloor.

The first stage of the observatory consisted of deploying an advanced circulation obviation retrofit kit (ACORK). Between 0115 h and 1245 h on April 15, we assembled a 279 m long ACORK casing string, consisting of 22 joints of 10¾ inch casing, two casing joints with 2 m tall screens for pressure monitoring, and an umbilical with three ¼ inch diameter tubes (only two of which were used) secured on the outside of the casing. The umbilical tubes were terminated at the two screens centered at 264 and 124 m below seafloor, respectively. Next, we assembled a drilling assembly inside the ACORK casing, composed of a 9⅞ inch drill bit, an underreamer with arms set to 14 inch diameter, and a mud motor to rotate the bit and underreamer in isolation from the casing. Finally, the umbilical tubes were connected to the valves and loggers on the ACORK wellhead, and the entire ACORK assembly was lowered to the seafloor at 2130 h on 15 April. Hole U1519B was reentered at 2310 h, and the ACORK wellhead landed in the reentry cone on the seafloor at 0635 h on 16 April. Once the ACORK had been released, we deployed a free-fall funnel (FFF) on top of the ACORK body. The ACORK casing was reentered with a 9⅞ inch drill bit and cleaned of cuttings on 16 April before installing a bridge plug on 17 April inside the ACORK casing at 277 mbsf to seal its interior from the formation below.

The second stage of the observatory consisted of deploying a CORK-II inside the ACORK. The 269 m long CORK-II casing string consisted (from top to bottom) of 20 full joints and four pup joints of 4½ inch casing, four 6¾ inch drill collars, and a bull nose. The CORK-II wellhead was attached, the entire assembly was lowered to the seafloor, and it reentered the ACORK funnel at 0120 h on April 18. We lowered the CORK-II wellhead until it reached a position ~20 m above the ACORK funnel.

The third stage of the observatory installation consisted of deploying a string of temperature sensors inside the CORK-II casing. At 0230 h on 18 April, we started assembling the 268 m long instrument string, which consists (from top to bottom) of a top plug, a single segment of Spectra rope with 15 miniature temperature loggers, one weak link, and one sinker bar. The instrument string was deployed using the logging wireline, and the top plug latched inside the CORK-II wellhead at 0530 h on 18 April. Once the instrument string was released, the CORK-II landed inside the ACORK wellhead and was released at 0735 h on 18 April, completing the observatory installation in Hole U1519B.

Hole U1519C

The primary coring objective at Site U1519 was to sample sediments in the intervals surrounding the ACORK pressure screens, which are centered at 124 and 264 m, and in the sedimentary section from ~520 to 640 mbsf. The vessel was offset 20 m from Hole U1519B at a heading of 122°, and Hole U1519C (38°43.6483′S, 178°36.8773′E, 1000.3 mbsl) was started at 1640 h on 18 April. Drilling without core recovery continued to 108 m until 0600 h on 19 April. RCB Cores 2R–7R, 9R–12R, and 14R–26R advanced from 108.0 to 640.0 m and recovered 119.17 m (55%). Intervals 163.6–250.0 m and 288.4–518.4 m were drilled without core recovery. The drill string was recovered at 0815 h on 21 April and the RCB BHA was put away.

Hole U1519D

The final objective at Site U1519 was to core the shallow sedimentary section and collect in situ temperature measurements with the APCT-3. The vessel was offset 10 m at a heading of 122°, and Hole U1519D (38°43.6516′S, 178°36.8831′E, 1000.4 mbsl) was started at 1505 h on 21 April. APC Cores 1H–3H advanced from 0 to 23.2 m and recovered 23.64 m (101%). Nonmagnetic core barrels were used for all APC cores. Because coarse unconsolidated material made it difficult to collect in situ temperature measurements and resulted in a partial stroke and significant overpull with Core 3H, we started a new hole.

Hole U1519E

The vessel was offset 20 m at a heading of 122°, and Hole U1519E (38°43.6572′S, 178°36.8949′E, 1000.3 mbsl) was started at 1845 h on 21 April. APC Cores 1H–8H and half-length APC (HLAPC) Cores 9F–13F advanced from 0 to 85.8 m and recovered 88.75 m (103%). Nonmagnetic core barrels were used for all cores. Formation temperature measurements were taken with the APCT-3 for Cores 4H–8H, 9F, 11F, and 13F.

Principal Results

Lithostratigraphy

We identified two lithostratigraphic units at Site U1519. Detailed characterization of lithofacies was hampered by large coring gaps, poor recovery, and pervasive coring disturbance. Overall, the sedimentary strata range in age from Holocene to early Pleistocene. Common lithologies include mud(stone), silt(stone), and sand(stone).

Coring of lithostratigraphic Unit I started at the seafloor in Holes U1519D and U1519E and at 108 mbsf in Hole U1519C. The unit extends to 282.66 mbsf. Cores over this depth range contain a background of dark greenish gray mud and mudstone (silty clay to clayey silt) with variable levels of consolidation. Seismic reflection records and high-resolution bathymetry are indicative of shallow, mass-transport remobilization at Site U1519. The APC cores from Holes U1519D and U1519E, however, reveal nothing definitive in terms of diagnostic indicators of gravity-driven, soft-sediment deformation within the hemipelagic mud.

The boundary between Units I and II at 282.66 mbsf displays a noticeable change in color from dark greenish gray above to light greenish gray below, the grain size coarsens somewhat to silt-rich mudstone, and there is a positive excursion in magnetic susceptibility. Below a 230 m gap in coring, mudstone occurs, with scattered thin interbeds of dark gray sandy siltstone to very fine sandstone. In Cores U1519C-19R, 21R, and 22R, the mudstone displays clear evidence of soft-sediment deformation, including convolute laminae, mesoscale folds, dismembered bedding, and clasts of mudstone supported by a mudstone matrix. We interpret the deformed zones as intraformational mass transport deposits (MTDs). The remainder of Unit II consists of consolidated greenish gray mudstone interbedded with poorly indurated sandy silt and sand, ranging up to coarse sand. Core 23R contains a distinctive matrix-supported conglomerate with widely dispersed clasts of mudstone and intact shells of what appear to be shallow-water fauna.

Biostratigraphy

Calcareous nannofossil and planktonic foraminifer species indicate that the sedimentary sequence recovered at Site U1519 is Holocene to Pleistocene. The base of the Holocene was identified between Samples 375-U1519E-1H-CC, 8–18 cm (4.40–4.50 mbsf), and 2H-CC, 14–24 cm (14.00–14.10 mbsf). The underlying section down to Sample 375-U1519C-15R-CC, 10–19 cm (536.32–536.41 mbsf), is dated late to middle Pleistocene (0.009–0.62 Ma), indicating a sedimentation rate of 0.84 m/ky. The age to the base of Hole U1519C is poorly constrained but is likely early Pleistocene or younger (<1.73 Ma).

Highly variable planktonic foraminifer abundances in the upper part (0–536.41 mbsf; through U1519C-15R-CC, 10–19 cm) fluctuate between outer neritic and oceanic environments. This variability is attributed to downslope reworking, evident from the co-occurrence of inner shelf benthic taxa and shell fragments with mid-bathyal markers. In the lower part of the section (546.86–635.65 mbsf; through 26R-CC, 0–5 cm), benthic markers indicate deposition in mid–lower bathyal or deeper water depths.

Paleomagnetism

The paleomagnetic analyses at Site U1519 were compromised by severe core disturbance, which destroyed the depositional remanence in the majority of cores. We thus only analyzed RCB cores below 525 mbsf in Hole U1519C, and APC cores from Holes U1519D and U1519E. Cores U1519C-14R to 26R were subjected to stepwise alternating field (AF) demagnetization to peak fields of 30 or 40 mT. Overprinting of the primary natural remanent magnetization (NRM), most likely by diagenetic alteration, and deformation in MTD intervals make shipboard magnetostratigraphy difficult.

Cores from Holes U1519D and U1519E were subjected to AF demagnetization to a peak field of 20 mT, which was sufficient to remove a small viscous overprint. The NRM directions usually have negative inclinations that agree with the directions expected for a normal polarity field. However, the data have not been corrected for core disturbance, and many APC sections were affected by significant drilling-induced bed drag. As a result, the downhole variations in NRM directions do not necessarily reflect time variations in the ambient magnetic field during deposition.

Structural Geology

Cores were recovered from four cored intervals at Site U1519. Intense drilling disturbance and lack of recovery limited recognition of structural features. However, dip data from logging-while-drilling (LWD) measurements conducted during Expedition 372 provide useful context for observations of core structures. Much of the strata at Site U1519 are inclined, although bed dips rarely exceed 50° in the cored intervals. Steeper beds are recorded in folded strata, which likely represent MTDs. We define two structural domains based on structures in the core and LWD data. In Domain 1, bedding dips are dominantly steep and there are scattered, steep, dominantly conductive fractures. Filled fractures are abundant within the lower recovered interval of Domain 1. Domain 2 coincides with the bottom of lithostratigraphic Unit II, and is defined by a decrease in the number of filled fractures, a slight shallowing of bedding dips in core, and a change in regional dip azimuth from north–northeast toward the north–northwest.

Geochemistry

A total of 100 whole-round (WR) samples were collected and squeezed for shipboard and shore-based pore water chemical analyses. We collected 31 samples from RCB cores in Hole U1519C, 15 samples from APC cores in Hole U1519D, and 54 samples from Hole U1519E. WR samples were collected on the catwalk at a frequency of six per core in the upper ~20 mbsf, and ~1–4 per core below 20 mbsf.

The geochemical profiles at Site U1519 reflect the combined effects of organic matter diagenesis, authigenic carbonate precipitation, and silicate mineral/volcanic ash alteration in response to high sedimentation rates. The pore water profiles of sulfate, alkalinity, ammonium, bromide, and phosphate in lithostratigraphic Unit I show characteristic changes with depth related to organic matter degradation. The shallow pore water sulfate profiles in Holes U1519D and U1519E are S-shaped, indicating a recent period of rapid sedimentation. This is also indicated by the alkalinity profile between the seafloor and the sulfate–methane transition zone (SMTZ). This recent sedimentation event has produced a deeper SMTZ than would be observed under steady-state sedimentation. As a result, the SMTZ at Site U1519 is at ~7–8 mbsf, similar to that observed at the frontal accretionary wedge Site U1518.

We observe a sharp increase in ammonium, alkalinity, phosphate, and bromide concentrations across the Unit I/II boundary, indicating that a second concentration maxima occurs within Unit II. The depth of the second concentration maxima is unknown due to the coring gap between 285 and 520 mbsf. The concentrations of these species, which are related to organic matter diagenesis, remain elevated in the cored interval from 520–635 mbsf but decrease with depth.

Dissolved calcium concentrations decrease sharply from 9.5 mM at 1.4 mbsf to 3.8 mM at the SMTZ. Below the SMTZ, calcium concentrations increase to 6.3 mM at 70 mbsf. The reversal in the Ca profile below the SMTZ suggests enhanced silicate mineral/volcanic ash alteration in the zone of microbial methanogenesis, leading to a net addition of Ca to the pore water despite co-occurring removal in authigenic carbonates. Likewise, there is an increase in strontium concentrations below the SMTZ to 130 μM (50% greater than seawater value), an increase in boron concentrations to ~750 μM (79% greater than seawater value), and a steady decrease in potassium concentrations, consistent with silicate and/or volcanic ash weathering in the upper 100 m of Unit I. There is a second interval of enhanced silicate mineral/volcanic ash diagenesis between 520–630 mbsf in Unit II.

Chloride concentrations are lower than average modern seawater value (559 mM) in the upper portion of Unit I, increasing from 549 mM at 1.4 mbsf (2% lower than average seawater value) to 559 mM at 17 mbsf. Between 17 and 120 mbsf, Cl concentrations remain relatively constant at or near seawater value. Likewise, sodium concentrations are also 2% lower than average seawater value between the seafloor and 17 mbsf, but remain low throughout Unit I. Chloride concentrations decrease from 550 to 534 mM across the Unit I/II boundary, and are low ranging from 440 to 546 mM between 520 and 630 mbsf. Discrete anomalies in the Cl profile at 520–630 mbsf are the result of methane hydrate dissociation during core recovery, marking zones of elevated methane hydrate concentrations. However, background Cl concentrations are lower throughout the 520–630 mbsf interval.

Between the seafloor and 144.3 mbsf, methane concentrations range between 0.55 and 5172.48 ppmv. Below 144.3 mbsf, methane concentrations in the headspace samples decrease and remain between 212.28 and 1802.82 ppmv, with an average concentration of 1011.35 ppmv. Ethane was detected in headspace samples below 520.53 mbsf and ranges between 0.25 and 1.92 ppmv. The methane-to-ethane ratios are consistently >500, indicating a dominantly microbial methane source. Organic C values in Units I and II range from 0 to 1.2 wt% (average 0.39 wt%). Inorganic C and total nitrogen concentrations slightly increase with depth in both lithologic units and range from 0.05 to 1.95 wt% (average 1.1 wt%) and from 0.00 to 0.09 wt% (average 0.05 wt%), respectively. The C/N ratios range from 0.85 to 14.92.

Physical Properties and Downhole Measurements

Natural gamma radiation (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) bulk density, and *P*-wave velocity were measured using the Whole-Round Multisensor Logger (WRMSL). Thermal conductivities were measured on WR core sections. Discrete *P*-wave velocity, moisture and density (MAD), and undrained shear strength were measured on working-half sections. MAD porosity values decrease from 74% near the seafloor to ~40% at 85 mbsf. At 109–135 and 250–284 mbsf, porosity values are nearly constant at 41%–45% and 37%–43%, respectively. Between 520 and 635 mbsf, porosity values show a slight increase with depth and range between 34% and 48%. *P*-wave velocity values range from 1500 to 1600 m/s between 0 and 10 mbsf, but the data are considered unreliable for the rest of the borehole.

Undrained shear strength values increase linearly from 0 to ~180 kPa with an average depth-dependent gradient of 2.5 kPa/m between 0 and 85 mbsf in Holes U1519D and U1519E. In Hole U1519C, the shear strength remains mostly constant with an average value of ~62 kPa between 105 and 140 mbsf, 30–300 kPa between 250 and 290 mbsf, and 54–1104 kPa between 515 and 555 mbsf. NGR values range from ~0 to 70 counts/s in Hole U1519C, and are relatively uniform through the cored intervals with an average of 40 counts/s. MS values are nearly constant between 0 and 150 mbsf and range from 10×10^{-5} to 30×10^{-5} SI except for a few ash layers where MS reaches values as high as 300×10^{-5} SI. Between 250 and 283 mbsf, MS values range from 15×10^{-5} to 20×10^{-5} SI and increase to $40–50 \times 10^{-5}$ SI at 283 mbsf, which corresponds with the lithostratigraphic Unit I/II boundary.

Thermal conductivity values range from 0.8 to 1.6 W/(m·K) between the seafloor and 80 mbsf. Between 109 and 135 mbsf, thermal conductivity values are uniform at ~1.3 W/(m·K), and at depths >250 mbsf increase to ~1.4 W/(m·K). APCT-3 measurements yield in situ temperature values from 6.44°C at 31 mbsf to 7.91°C at 86 mbsf, which correspond to a thermal gradient of 24.3°C/km. Using a mean thermal conductivity value of 1.31 W/(m·K), the heat flow is estimated as ~33 mW/m^2.

Core-Log-Seismic Integration

LWD data acquired during Expedition 372 in Hole U1519A were correlated with core-based observations and physical properties measurements from Holes U1519C–U1519E, and with seismic reflection data across the site in the North Tuaheni Basin. These different data sets detect variations in physical properties, lithology, and structure at a range of scales. LWD *P*-wave velocity and density measurements were used to develop a synthetic seismic trace to correlate the LWD, core, and seismic data. This allowed us to assess the match between the seismic traces that would be predicted from the physical properties in the boreholes with the actual seismic sections acquired across Site U1519 prior to the expedition. Based on the new seismic tie, we revised the precise boundaries of the three major seismic units defined by Expedition 372 scientists, and compared these units with LWD and lithologic units from Expedition 375.

The upper seismic unit is 281 m thick and comprises a horizontal basin-fill sequence, including at least two major MTDs in the upper 141 mbsf and a thick underlying section of inferred sandy sediments that were not cored. Cores from recovered intervals in this unit comprise mudstones with minor sand and volcanic ash and are <0.54 Ma. Both observatory screens were deployed in silty mudstone intervals in this unit. The middle seismic unit is a seaward-dipping, 265 m thick slope sequence, partially buried by the upper seismic unit. This interval includes a mixture of layered sediments and MTDs, as interpreted from seismic data. Only the upper 3.5 m and lower 27 m of this sequence were cored and consist of predominantly fine-grained mudstone. The lower seismic unit is a strongly reflective interval that dips landward as a result of uplift and tilting by thrust faulting beneath the site. Cores recovered from this unit to depths of 635 mbsf consist of mudstone and sandy MTDs, which have been dated at 0.54–1.73 Ma, younger than the expected Miocene/Pliocene age that was based on interpretation of seismic reflection data prior to drilling.