IODP Expedition 375: Hikurangi Subduction Margin

Site U1518 Summary

Background and Objectives

Site U1518 is located on the lower continental slope near the trench and ~73 km from shore in ~2630 m water depth. This site is located on the forelimb of an anticline formed by an out-of-sequence thrust branching from the plate interface. The thrust is thought to accommodate a component of plate motion in this portion of the Hikurangi margin, and it is possible that it hosts slow slip events. Expedition 372 collected logging-while-drilling (LWD) data in Holes U1518A and U1518B in December 2017. Coring at Site U1518 during Expedition 375 was intended to penetrate into the out-of-sequence thrust, terminating 150–200 m into the footwall of the fault. Drilling was expected to encounter accreted Pleistocene trench-fill sediments comprising sand and mud turbidites, ash, and mass transport deposits in both the hanging wall and footwall of the thrust. The primary objectives at this site were (1) coring to total depth, with the highest priority to sample the lower ~100 m of the hanging wall, the fault zone, and the footwall of the thrust (including additional possible faults within the footwall suggested on the basis of seismic and LWD data); and (2) installation of a subseafloor observatory to monitor changes throughout the slow slip cycle within and surrounding the fault zone.

The main scientific objectives of coring at Site U1518 were to define the structures and deformation, physical properties, lithology and composition, and interstitial fluid geochemistry of the out-of-sequence thrust fault and surrounding sediments. Coring results were used in combination with LWD data to define the depth interval for observatory pore pressure monitoring and geochemical sampling in the fault zone and to select optimal locations for pore pressure monitoring in the hanging wall and footwall. The observatories will monitor formation pore pressure changes (as a proxy for volumetric strain), and the evolution of physical, hydrological, thermal, and chemical properties and conditions throughout the slow slip cycle using a string of temperature sensors and an OsmoSampler and Osmoflowmeter installed within the fault zone.

The key foci for postexpedition studies on core samples include (but are not limited to): (1) structural analyses to characterize deformation mechanisms and style, and fracture and fault orientations; (2) fault and wall rock rheology and friction to test hypotheses linking fault constitutive properties to slip behavior; (3) geomechanical and thermal properties measurements to define poroelastic, strength, and heat transport properties of the formation to guide interpretation of observatory data; and (4) measurements of strength, permeability, and elastic moduli to provide context for the interpretation of borehole failures as indicators of in situ stress magnitude, parameterization of hydrological models, and core-log-seismic integration.

Operations

Transit to Site U1518

The *JOIDES Resolution* departed from Timaru, New Zealand, at 0728 h (UTC + 13 h) on 11 March and arrived at Site U1518 (proposed Site HSM-15A) at 1900 h on 13 March.

Holes U1518C and U1518D

Hole U1518C (38°51.5692′S, 178°53.7616′E, 2631.7 m below sea level [mbsl], 2642.4 m below rig floor [mbrf]) was started at 0905 h on 14 March 2018 with an advanced piston corer/extended core barrel (APC/XCB) bottom-hole assembly (BHA). A full core barrel was retrieved following a partial stroke and the hole was abandoned to attempt another mudline core. The bit was raised 3 m and Hole U1518D (38°51.5699′S, 178°53.7634′E, 2628.2 mbsl, 2638.9 mbrf) was started at 1020 h. Another full core barrel was retrieved and this hole was also abandoned.

Hole U1518E

The vessel was offset 5 m to the North, the bit was raised another 3 m, and Hole U1518E was started at 1125 h on 14 March 2018 (38°51.5669′S, 178°53.7618′E, 2626.1 mbsl, 2636.8 mbrf). Cores 1H to 32X penetrated from 0 to 175.6 mbsf and recovered 160.96 m (92%). Advanced piston corer temperature tool (APCT-3) formation temperature measurements were taken with Cores 4H, 6H, 8H, 10H, and 14F. The decision was made to switch to coring with the rotary core barrel (RCB) after discovering that the cutting shoe used with Core 31X had been destroyed after it took 80 min to advance 3.6 m while cutting Core 32X.

Hole U1518F

The vessel was offset 5 m to the south. Hole U1518F (38°51.5694′S, 178°53.7619′E, 2626.1 mbsl, 2636.8 mbrf) was started at 0135 h on 17 March 2018 with an RCB BHA, and was advanced without coring to 197.7 mbsf. Cores 2R–32R penetrated from 197.7 to 494.9 mbsf and recovered 126.82 m (43%). Coring was terminated so that observatory operations could start.

Hole U1518G

In preparation for installing the observatory, we decided to predrill the observatory hole. The vessel was offset 35 m north of Hole U1518F (and ~5 m south of Hole U1518B). A BHA with a 14¾ inch drill bit was lowered to the seafloor, and Hole U1518G (38°51.5505′S, 178°53.7617′E, 2629.8 mbsl, 2640.5 mbrf) was started at 1050 h on 20 March 2018 and continued to 433 mbsf. 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 2000 h on 22 March and 1700 h on March 23, we assembled a 422 m long ACORK casing string consisting of 10¾ inch casing, three joints with pressure screens, and an umbilical with three ¼ inch-diameter tubes secured on the outside of the casing. The umbilical tubes were terminated at the three screens centered at 393, 323, and 218 mbsf, respectively, to monitor pressure below, within, and above the fault zone. 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 on 24 March. During our attempt to reenter Hole U1518G, unexpected heave caused the drill bit to hit the reentry cone at 1215 h. This resulted in the cone and its base being offset ~7 m from the hole, making reentry into the predrilled hole impossible.

Hole U1518H Observatory

With the underreamer and drill bit inside of the ACORK casing and the entire assembly already at the seafloor, the decision was made to drill in the ACORK assembly at the new location. Hole U1518H (38°51.5402′S, 178°53.7642′E, 2631.1 mbsl, 2642.0 mbrf) was started at 1245 h on 24 March, and reached a total depth of 427 m. Once the ACORK landed in the reentry cone, we deployed an ROV platform and a free-fall funnel on top of the ACORK body. The ACORK casing was reentered and cleaned of cuttings on 26 March before installing a bridge plug on 27 March at 421 m inside the ACORK casing to seal its interior from the formation.

The second stage of the observatory consisted of deploying a CORK-II inside the ACORK but operations were interrupted on 28 March while we waited for the R/V *Tangaroa* to deliver replacement seals. During this period we relocated to Site U1520 to drill in a reentry system, in advance of coring there later in the expedition. We resumed operations at Hole U1518H on 31 March by assembling the 412 m long CORK-II casing string, consisting of 4½ inch drill pipe, two swellable-packer joints, one quadrant-seal joint carrying the seat for the OsmoSampler package, drill collars, and a bull nose. The CORK-II wellhead was attached on 1 April and the entire assembly was lowered to the seafloor until it reentered the ACORK funnel and the CORK-II wellhead reached ~17 m above the ACORK funnel.

The third stage of the observatory consisted of deploying the temperature sensors and OsmoSampler package inside the CORK-II casing string. On April 1, we assembled the 407 m long instrument string, consisting of three segments of Spectra rope carrying a total of 24 miniature temperature loggers (MTLs), the ~22 m long OsmoSampler package with an additional seven MTLs inside, three weak links, four sinker bars, and the top plug. The instrument string was deployed with the logging wireline. At 2105 h on 1 April, the OsmoSampler package landed in the CORK-II seat at 323 mbsf, followed soon after by the top plug latching inside the CORK-II wellhead. Once the instrument string was released, the CORK-II landed inside the ACORK wellhead at 0020 h on 2 April, completing the observatory installation in Hole U1518H.

Principal Results

Lithostratigraphy

The sediments at Site U1518 comprise three lithostratigraphic units, two of which (Units I and III) were divided into two subunits. All three units are Quaternary in age. Sediment composition and texture are consistent throughout Holes U1518E and U1518F, with a background of silty clay(stone) or mud(stone) alternating with thin beds of silt(stone) to silty sand(stone). The distinctions among lithologic units are based largely on the character of coarser event beds (inferred to be turbidites) and soft-sediment deformation features (inferred to be mass transport deposits).

The uppermost 2.2 m of Core 375-U158E-1H consists of unconsolidated Holocene mud. Subunit IA begins below this mud and extends to 197.7 mbsf. Sediment from the core catcher of Core 1H has an age >0.54 Ma, and porosity is lower than expected for the current depth of burial. We therefore consider some of the original stratigraphic section to be missing due to submarine slides or other forms of mass wasting after frontal accretion. The normally graded beds range in grain size from sandy silt to silty sand and very fine sand. We surmise that relatively dilute turbidity currents were interspersed with background settling of suspended sediment on the trench floor of the Hikurangi Trough. Felsic ash layers also occur in the uppermost 44 m, and they were probably deposited by air fall. Subunit IB extends from 197.7 to 304.5 mbsf and is characterized by sparse and thinner (<10 cm) beds of normally graded siltstone. Its upper boundary is gradational. The position of the subunit boundary coincides with the bottom of the zone that was not cored.

Unit II extends from 304.5 to 370.4 mbsf. Its upper boundary matches a significant change in biostratigraphy, defined by a thrust-related age inversion with older hanging wall (>0.54 Ma) over younger footwall (<0.54 Ma) sediments. We designated this material as a separate lithologic unit on the basis of a sharp reduction in the number of silty turbidites, as well as a subtle change in color to lighter greenish-gray mudstone. The mudstone in Unit II alternates with thin but sparse layers of siltstone, sandy siltstone, and mud-rich nannofossil ooze.

Unit III begins at 370.4 mbsf and extends to the base of Hole U1518F (492.4 mbsf). This unit is composed of mudstone with thin beds of normally graded siltstone and sandy siltstone, and was deposited by turbidity currents and hemipelagic settling in a trench-floor environment. The most distinctive characteristic of Unit III is soft-sediment deformation, similar in many respects to what has been described in mass-transport deposits (MTD) from comparable depositional environments elsewhere (e.g., the Nankai Trough). We subdivided Subunits IIIA and IIIB based on a change in the spatial concentrations of the MTD-type features at 475.7 mbsf. The amount of soft-sediment deformation decreases significantly in Subunit IIIB; intricate varieties of bioturbation become more widespread and diverse below the subunit boundary.

Biostratigraphy

Planktonic foraminifer and calcareous nannofossil biostratigraphy shows that a Holocene to early Pleistocene sedimentary sequence was recovered at Site U1518. Due to high sedimentation rates (~3 m/ky), shipboard paleontological sampling achieved a temporal resolution of 1.5–3 ky from half-length APC (HLAPC) and APC cores.

The base of the Holocene was identified between Samples 375-U1518E-1H-2-W, 47–52 cm, and 1H-2-W, 83–88 cm (2.02–2.33 mbsf). The underlying section down to the base of the sediments comprising the hanging wall (Samples 375-U1518E-1H-2-W, 83–88 cm, through U1518F-12R-CC, 0–10 cm; 2.33–297.0 mbsf) is dated middle Pleistocene, and the footwall succession (Samples U1518F-13R-CC, 9–20 cm, through 32R-CC, 0–12 cm; 306.95–492.38 mbsf) is dated middle Pleistocene or younger.

Midbathyal benthic foraminifer markers occur throughout the sedimentary sequence, and very rare lower bathyal markers occur in a few footwall samples. The absence of lower bathyal markers in most samples is unexpected, given that the site was drilled in a water depth of 2626 m, suggesting that the bulk of the sedimentary sequence has been reworked downslope from midbathyal water depths or shallower. Downslope reworking is supported by the presence of common inner to midshelf taxa in some samples.

Paleomagnetism

At Site U1518 we established a magnetic polarity timescale based on magnetic inclination data. Routine analysis included measurement of the natural remanent magnetization (NRM) of archive-half sections prior to and following stepwise alternating field (AF) demagnetization to a peak field of 30 mT. Interpretation of the paleomagnetic results was compromised by the diagenesis of the primary magnetic mineral phases and extensive tectonic deformation. Some cores also experienced core disturbance that resulted in the complete destruction of the depositional remanence. All XCB cores were affected by significant drilling-induced overprints that could not be removed during routine demagnetization of the archive-half sections. More extensive AF and thermal demagnetization experiments were conducted on discrete specimens to aid our interpretation. Inclination records show that the entire sequence recovered at Site U1518 is most likely of normal polarity, despite an interval between 220 and 270 mbsf in which the polarity remains unresolved. Based on biostratigraphic observations we place the paleomagnetic record in the Brunhes Chron (C1n).

Rock magnetic analyses included the determination of the magnetic coercivity distribution based on AF demagnetization, isothermal remanence (IRM) acquisition, and the measurement of magnetic susceptibility. Inferences about the blocking temperature (Tb) distribution of individual samples were drawn from the thermal demagnetization behavior. We did not observe any significant variations in the rock magnetic properties downhole, although the uneven sampling through the fault zone, for example, means that we may not have fully resolved rock magnetic variations. We tentatively identify least two magnetic mineral phases. The first is a low coercivity (≤50 mT) mineral that we suggest is Ti-magnetite. During AF demagnetization experiments the majority of our samples were affected by the growth of a gyroremanence at treatment steps higher than 50 mT, which we attribute to the presence of greigite caused by diagenesis.

Structural Geology

Hole U1518E consists of sediments with gently to moderately dipping beds, although significant drilling-induced deformation in the APC and XCB cores prevent detailed structural observations. RCB cores in Hole U1518F preserve a suite of deformation structures that span the main thrust fault and a subsidiary fault. Gently to steeply dipping beds, locally overturned, were observed within the hanging wall. Bedding dip trends within the hanging wall generally agree well with LWD-derived bedding dips. These beds are crosscut by moderately to steeply dipping fractures that increase in frequency with depth toward the fault zone. Normal faults, with centimeter-scale displacements, are also preserved at scattered locations throughout the sequence.

The fault zone was recognized in Cores 375-U1518F-13R to 15R by intense brecciation, discrete fractures, and the occurrence of ductile deformation zones. Several of the apparently ductilely deformed zones are overprinted by brittle structures. The intensity of deformation decreases gradually towards the base of the fault zone. There is a general change from dominantly brittle to dominantly brittle/ductile deformation from the hanging wall to the footwall. The ductile deformation is likely a composite of tectonic, synsedimentary, and slope processes.

The footwall of the fault is characterized by relatively undeformed hemipelagic sediments with modest and relatively constant dip angles, cut by a few normal faults and fractures. This package hosts another zone of more intense deformation and brecciation, indicating a second fault in Cores U1518F-18R and 19R. There is no clear change in lithology across the second fault. Below this zone, bedding dips are generally gentle, again in general correspondence with LWD-derived bedding dips, and deformation structures are few.

Geochemistry

We collected 82 whole-round (WR) samples for pore water chemical analyses at Site U1518. Samples were collected on the catwalk at a frequency of six WRs per core from the seafloor to 17.9 mbsf, three WRs per core to 27 mbsf, and ~1–2 WRs per core from 27 to 494.9 mbsf. Each core collected below 30 mbsf was scanned with an infrared (IR) camera, in order to identify cold anomalies suggesting potential methane hydrate occurrence. The majority of the WR samples were taken away from the IR anomalies to establish in situ background chemical profiles not impacted by methane hydrate dissociation during core recovery. A small subset of WR samples corresponding to IR cold anomalies were analyzed to quantify methane hydrate saturations based on deviation of dissolved chloride concentrations from the background profile. Drilling fluid was also analyzed as part of the shipboard geochemical program to aid in identification of potential contamination; below the sulfate–methane transition zone (SMTZ), sulfate is depleted in the pore water, and any sulfate present in a sample is the result of contamination with drilling fluid. Based on the SO_4 concentration of each pore water sample below the SMTZ, we corrected all pore water species for drilling contamination.

The pore fluid chemical profiles at Site U1518 reflect the combined effects of microbially mediated organic matter degradation, authigenic carbonate precipitation, volcanic ash alteration, and silicate mineral diagenesis. Sulfate concentrations decrease almost linearly from 28.1 mM at 1.5 mbsf to below detection limit (0.1 mM) at ~8 mbsf. The SMTZ is marked by a concomitant increase in headspace methane concentrations from 51 to 5,461 ppmv. The shallower SMTZ at this site in comparison to nearby IODP Expedition 372 Site U1517 likely indicates a higher vertical methane flux. Ethane was detected in some headspace samples above 200 mbsf, but was not detected below this depth. The methane is microbial in origin with C_1/C_2 ratios >20,000.

The alkalinity, ammonium, bromide, and phosphate concentration profiles also reflect organic matter diagenesis with peaks in concentrations within lithostratigraphic Subunit IA, followed by a decrease in concentration within Subunit IB. The fault zone coincides with a repetition of the diagenetic sequence in the footwall with a second peak in alkalinity, ammonium, and phosphate concentrations in Unit III. Based on the deviation of Cl concentrations from the background concentration profile, we identified the presence of methane hydrates in six WR samples.

Chloride, potassium, and sodium concentrations increase with depth and reach concentration maxima at ~60 mbsf in Subunit IA. Likewise, silica, lithium, and strontium concentrations steadily increase within Subunit IA, then decrease between the top of Subunit IB and the fault zone at ~300 mbsf. The sediments of Subunit IA contain several volcanic ash layers, disseminated ash, and have elevated concentrations of K-feldspar. The increase in pore water Cl, alkali metal, and strontium concentrations within this unit likely reflects ongoing alteration of rhyolitic ash and K-feldspar to authigenic hydrous aluminosilicate minerals. Similar to the geochemical tracers of organic matter diagenesis discussed above, there is a clear repetition of the ash/silicate mineral diagenetic sequence below the fault zone.

Analyses of the solid phase yielded $CaCO_3$ values ranging from 2.1 to 23.1 wt%. Total organic carbon (TOC) concentrations are generally low and range from 0.1 to 0.88 wt%. The C/N ratios range from 0.85 to 15.80 (average of 6.84). Localized peaks in the C/N ratio occur in Unit II, suggesting more heterogeneity in organic matter sources within this depth interval.

Physical Properties

In general, a significant change in physical properties is observed between 0 and 50 mbsf in Hole U1518E. Below 50 mbsf, all physical properties are nearly constant with depth, with some specific exceptions. The depth trends of bulk density, porosity, *P*-wave velocity, and natural gamma ray measured in the cores are less pronounced than LWD bulk density, neutron porosity, *P*-wave velocity, and gamma ray data.

Porosity decreases from 65% to 50% within the top 50 m. Between 50 and 495 mbsf, porosity is nearly constant and ranges from 40%–50%. A modest increase in porosity with depth is observed at 300–370 mbsf, corresponding to the interval spanning the main thrust and subsidiary fault zones, and where extensive deformation is observed. Thermal conductivity is relatively constant with depth and has an average value of 1.38 ± 0.10 W/(m·K). *P*-wave velocity is ~1500 m/s near the seafloor and increases rapidly to 1600 m/s at 2 mbsf. Between 2 and 12 mbsf, *P*-wave velocity is approximately constant at 1600 m/s followed by a gradual increase to 1950 m/s at 150 mbsf. Below 238 mbsf, *P*-wave velocities are scattered and range from ~1500 to ~2000 m/s.

Natural gamma ray (NGR) values range from 6 to 63 counts/s, with an average of 42 counts/s. NGR rapidly increases from <25 count/s at the seafloor to 40 count/s at 2 mbsf. Below 2 mbsf, NGR is nearly constant with an average value of 42 count/s. Magnetic susceptibility (MS) values are correlated with the lithostratigraphic units. The depth interval between 2 and 176 mbsf (in lithostratigraphic Subunit IA), is characterized by zones of low MS and little scatter with an average value of 11–14 × 10^{-5} SI (2–12, 40–60, and 75–109 mbsf), and intervening zones of high MS and high scatter with an average value of 22–25 × 10^{-5} SI (13–40, 60–75, and 109–176 mbsf). Between 197.7 and 462 mbsf, from the top of Subunit IB to the bottom of Subunit IIIA, MS values exhibit some scatter but less than observed in Subunit IA, ranging from 10 × 10^{-5} to 20 × 10^{-5} SI. Susceptibility shifts to a lower average value of 13 × 10^{-5} SI at 466 mbsf, and remains constant to 490 mbsf (in Subunit IIIB).

Downhole Measurements

Five formation temperature measurements were taken with the APCT-3 in Hole U1518E while taking Cores 4H, 6H, 8H, 10H, and 14F. Although all five measurements are of high quality, there is an offset between the three measurements taken with one sensor and the two taken with another. We estimate a thermal gradient of 0.035°C/m as a function of the depth using three equilibrium temperatures from one of these tools. The thermal conductivity is relatively constant with depth and has a value of 1.38 W/(m·K). The vertical conductive heat flow computed as the product of the thermal gradient and thermal conductivity is 48 mW/m^2. The temperature at 304 to 324 mbsf corresponding to the thrust fault is estimated to be 12° to 13°C.

Core-Log-Seismic Integration

LWD data acquired during Expedition 372 in Holes U1518A and U1518B were correlated with core-based observations and physical properties measurements from Holes U1518E and U1518F, and with seismic reflection data across the holes drilled at Site U1518. 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 combined with density measurements from cores to develop a synthetic seismic trace to correlate the LWD, core, and seismic data. The synthetic seismic trace using the LWD data correctly predicts moderate amplitude reflections in the upper 80 mbsf, low amplitude reflections down to ~300 mbsf, and a package of high amplitude reflections between 300 and 400 mbsf.

However, a significant reduction in LWD density and velocity around 322 mbsf produced a high-amplitude reverse polarity reflection in our synthetics that is ~15–20 m too deep compared to a real high-amplitude reverse polarity reflection in seismic profile 05CM-04 at the location of Hole U1518F. This high amplitude reflection separates truncated reflections above from continuous parallel reflections below. Core physical property measurements show a reduction in density around 300–315 mbsf, shallower than that observed in the LWD data. Together, the core laboratory measurements and seismic data suggest that the fault zone in the cored section at Hole U1518F lies 15–26 m shallower than the same change in properties identified in the LWD data at Hole U1518B. This is supported by a better matching synthetic seismic trace when the LWD reduction in density and velocity is shifted 15 m shallower. The difference in fault zone depth between Holes U1518F and U1518B may be due to thrust fault geometry.