IODP Expedition 362: Sumatra Seismogenic Zone

Site U1480 Summary

Background and Objectives

Site U1480 (proposed Site SUMA-11C) is located on the Indian oceanic plate, east of the Ninety East Ridge and west of the North Sumatran subduction margin. The primary drilling objective at Site U1480 was to recover a complete section of the oceanic plate sedimentary section and the uppermost basaltic basement. Moving toward the trench, this section is overlain by a rapidly deposited trench wedge and is eventually subducted at the margin offshore North Sumatra. The sedimentary section is 4–5 km thick at the subduction deformation front. Based on pre-expedition seismic interpretation, the sedimentary section at Site U1480 includes: a thin section of seismic Unit 1 (the distal onlapping element of the trench wedge); the Nicobar submarine fan sequence of seismic Unit 2; and the pelagic pre-fan seismic Unit 3. This site was targeted for drilling as it provides constraints on the initial physical, chemical, thermal, and mechanical properties of the complete input section, and potentially the state of stress of the lower part of this input section within which the earthquake-generating plate boundary fault eventually develops. These constraints also allow us to understand the materials that may control the properties generating the unusual wide forearc plateau. The section thickens significantly on approaching the subduction zone, therefore postexpedition experiments and numerical modeling will be conducted to evaluate the impact of increasing burial, temperature, and diagenetic alteration on material properties. Site U1480 will therefore allow us to address the primary expedition objectives to determine how the properties of the input section may lead to shallow seismogenic slip and to unusual forearc/prism development. Site U1480 also offers the opportunity to obtain a complete section of the Nicobar Fan sequence at 3°N where the onset of fan deposition was expected to be ~30–40 Ma based on interpolation between previously drilled sites. The Nicobar Fan is separated from the Bengal Fan by the Ninety East Ridge and understanding fan onset and growth is important for a complete sedimentary history of deposition related to Himalayan uplift, erosion, and monsoon development.

Site-specific objectives were:

- To identify the principal lithologies that may be involved in development of the plate boundary fault.
- To establish how the mechanical/strength properties of the different lithologies change with depth to determine trends and the effects of burial rate and time, and to identify potential discontinuities that may be candidates for detachment positions.
- To identify any thermal history indicators, and any effects of early diagenesis, and to

establish the present day thermal structure of the section.

- To identify fluid sources and changes with depth.
- To determine the primary sources of sediment delivered to the site (in particular seismic Units 1 and 2) and changes in source with time. Potential sources include: the Himalaya and Ganges Brahmaputra floodplain via the Bengal fan system, the Irrawaddy fed by the Indo-Burman range, the Sunda forearc, the Sumatran mainland (including volcanic arc), and the Ninety East Ridge.

Operations

The *JOIDES Resolution* completed the 842 nmi transit from Colombo, Sri Lanka, in 65.8 h at an average speed of 12.8 kt. The vessel arrived at Site U1480 at 0615 h on 12 August 2016 (all times reported are ship local time, which is UTC + 7 h at Site U1480), and an acoustic seafloor-positioning beacon was deployed. Site U1480 is located at 3°2.04′N, 91°36.35′E, in a water depth of 4148 m, and consists of eight holes (U1480A–U1480H).

An advanced piston corer (APC)/extended core barrel (XCB) bottom-hole assembly (BHA) was made up, and Holes U1480A, U1480B, U1480C, and U1480D were spudded at 0050 h, 0235 h, 0400 h, and 0535 h, respectively. In each case, a full core was recovered and the hole was terminated because the mudline was missed. After correcting an error in the pipe tally and seafloor depth calculation, Hole U1480E was spudded at 0710 h on 13 August and APC Cores 1H–12H advanced to 99.7 m below seafloor (mbsf). Non-magnetic core barrels were used for all cores, and Cores 1H–8H were oriented with the Icefield MI-5 tool. APCT-3 formation temperature measurements were taken with Cores 6H, 8H, and 12H. One attempted temperature dual-pressure tool (T2P) deployment with the motion decoupled hydraulic delivery system (MDHDS) and the Electrical Release System (ERS) was unsuccessful.

Hole U1480F was spudded at 1910 h on 14 August 2016 and was drilled without coring from the seafloor to 98.0 mbsf. Non-magnetic core barrels and orientation were used for Cores 2H–8H. Coring continued with the half-length APC (HLAPC) system for Cores 9F–29F to 245.2 mbsf. APCT-3 formation temperature measurements were taken with Cores 4H, 6H, 13F, and 22F. Since all cores with the HLAPC system were also partial strokes, we began alternating 5 m drilled intervals with HLAPC cores to achieve penetration while still complying with safety guidelines. Cores 31F to 51F penetrated from 250.2 to 357.7 mbsf. Within that interval, the nature of the formation required using the XCB system for Cores 34X, 35X, and 37X. Continuous XCB coring resumed from Core 52X to 98X at a final depth of 815.0 mbsf.

Hole U1480G was intended to penetrate the deeper sedimentary section and 10 m into igneous basement. Operations started with the installation of a reentry system. First, we assembled 755.9 m of 10¾ inch casing and suspended it from the mud skirt, which was resting on the moonpool doors. Second, we assembled and tested a drilling assembly with a drill bit, an underreamer, and a mud motor; this was lowered through the casing hung in the moonpool. Third, ~687 m of 5 inch drill pipe was attached to the drilling assembly, followed by a Hydraulic Release Tool (HRT) that was secured on the casing hanger. Next, the casing with the drilling assembly and drill pipe within were lowered to ~150 m below the rig floor so that a free-fall funnel (FFF) could be dropped onto the HRT. Finally, the entire reentry system and drilling assembly was lowered to the seafloor and the subsea camera was deployed so that we could observe the reentry system while it was drilled into the seafloor. Hole U1480G was spudded at 0105 h on 23 August, and drilling continued until the reentry system landed on the seafloor at 1330 h on 24 August. The depth of the hole was calculated at 759.6 mbsf, with the end of casing at ~754 mbsf. The drilling assembly was released from the reentry system using the HRT and then recovered to the surface. Hole U1480G was reentered at 2005 h on 25 August with a rotary core barrel (RCB) BHA and Cores 2R–73R advanced from 759.6 to 1431.6 mbsf. In preparation for logging, the drill bit was released at the bottom of the hole and the hole was displaced with 300 barrels of heavy mud. As a result of poor hole conditions encountered below the casing, a shorter wireline logging tool string was run into the hole until it encountered an obstruction at 809 mbsf, ~52 m below the casing shoe. Logging data were collected from 809 mbsf to ~19 m above seafloor and the tool string was pulled to the surface and stored. Logging activities were completed at 1730 h on 5 September.

An APC/XCB BHA was made up and Hole U1480H was spudded at 1545 h on 6 September 2016. APC coring continued through Core 17H to 129.4 mbsf. Non-magnetic core barrels were used and the cores were oriented with the FlexIt orientation tool. Formation temperature measurements (APCT-3) were taken with Cores 4H, 7H, 10H, 12H, and 17H. The drill string was pulled out of the hole, and the vessel was prepared for transit to Site U1481. Site U1480 activities concluded at 0212 h on 8 September, and the total time spent on Site U1480 was 26.8 d.

Principal Results

Sedimentology and Petrology

Sediment and sedimentary rock were recovered from the seafloor to 1415.35 mbsf at eight holes (U1480A–U1480H). Beneath the sedimentary cover, a series of extrusive and intrusive rocks interbedded with volcaniclastic sediments are underlain by a thin interval (1415.35 to 1431.63 mbsf) of basaltic crustal rock of the igneous basement. The sediment represents the late

Cretaceous to Recent deep-marine sedimentary cover of the ocean floor between the Ninety East Ridge and the Sunda subduction zone.

Lithostratigraphic definitions for Site U1480 were based exclusively on cores recovered from Holes U1480E, U1480F, and U1480G. The sediments were mostly unlithified to semilithified, but in intervals near basement, lithified materials were encountered. The main lithologies are nannofossil-bearing mud, siliciclastic mud, and siliciclastic sand. Dominant siliciclastic lithologic variants are clay (clay-mineral dominated), silty clay, and fine-grained sand. Six lithologic units were identified (Units I–VI) based on major lithologic changes. Subunits were defined when minor, but distinct lithologic changes occurred within units. The overall succession consists of predominantly siliciclastic sediments interpreted as Nicobar fan underlain by mixed tuffaceous and pelagic sediments and a series of intercalated pelagic and igneous materials overlying ocean crust.

Unit I consists of Subunits IA, IB, and IC. Subunit IA (0–5.60 mbsf) is dominated by calcareous clay with minor biosiliceous and ash components. Subunit IB (5.60–18.80 mbsf) is characterized by fine-grained sand and clay, with minor calcareous clay and ooze. Subunit IC (18.80–26.42 mbsf) contains silty clay and calcareous clay with minor ash.

Unit II consists of Subunits IIA, IIB, and IIC. Subunit IIA (26.42–343.67 mbsf) comprises layers of thin- to medium-bedded, laminated to structureless sandy silt and fine-grained sand, with silty clay and silt. Subunit IIB (343.67–785.80 mbsf) contains alternating thin- to very thin-bedded, cross- and parallel-laminated silt and clay. Subunit IIC (785.80–1250.35 mbsf) is bioturbated black and dark gray clay/claystone and silty clay/claystone, and structureless muddy sand/sandstone with plant material and mud clasts.

Unit III consists of Subunits IIIA and IIIB. Subunit IIIA (1250.35–1310.02 mbsf) is dominated by foraminifer-bearing, gray-green and minor reddish-brown clay/claystone. Subunit IIIB (1310.02–1327.23 mbsf) is dominated by reddish-brown tuffaceous silty clay/claystone with biosiliceous debris and minor lithified calcareous ooze (chalk).

Unit IV (1327.23–1349.80 mbsf) comprises basaltic flows, tuffaceous and volcaniclastic sand/sandstone, and volcanic breccia.

Unit V (1349.80–1415.35 mbsf) is defined mainly on the basis of the reappearance of calcareous ooze (chalk) and calcareous clay/claystone intercalated with magmatic intrusions.

Unit VI (1415.35–1431.6 mbsf) is basalt interpreted as ocean crust consisting of fine- to medium-grained plagioclase- and pyroxene-bearing seriate-textured basalt with low vesicle content (<1%). An overall moderate to high alteration state is indicated by a brownish color and the occurrence of several mineral-filled fractures.

Structural Geology

Deformation structures at Site U1480 are rare, including the preservation of subhorizontal bedding dips. In a few instances bedding dips are >10°, and they are related to slumping. Sand and mud injections into overlying strata were also observed. Vein structures are identified at a number of intervals. Additionally, a limited 20 m interval in Eocene clay/claystone exhibited a variety of fault and shear zone structures, many of which appear in conjugate geometries. These cm-scale shear zones are oriented at a high angle to bedding. In this section, crosscutting fault relationships, fault-bedding cutoff angles, and crosscutting and overprinting relationships of diagenetic fabrics (flattened oxidation spots) lead us to interpret that this deformation occurred before or during the earliest parts of deposition of the overlying Nicobar Fan sequence. Although rare faults are observed in clusters in the overlying late Miocene Nicobar Fan interval, many can be associated with synsedimentary structures like recumbent isoclinal folds indicating slumping processes. We found no compelling evidence for deformation associated with the steep faults that cut the seafloor imaged on seismic reflection data near the site.

Careful description and analysis of the type and intensity of drilling deformation structures and drilling conditions were used to make qualitative assessments of formation strength and lithology. For example, a more stable and intact wellbore is suggested by lack of fall-in material at the base of Unit II, and is supported by the relative absence of drilling deformation structures. The most important finding from the preliminary evaluation of drilling conditions is the recognition of sand-rich sections in intervals of poor (<10%) recovery. Fast drilling appears to be correlated with high sand fractions, so intervals of low recovery with fast drilling are interpreted as sand-rich.

Biostratigraphy

The biostratigraphy of the ~1400 m thick sedimentary sequence cored at Site U1480 was based on calcareous nannofossils, planktonic foraminifers, diatoms, radiolarians, and silicoflagellates. Calcareous microfossils occurred discontinuously and mostly in low abundances throughout the sequence. Biosiliceous microfossils occurred in two short intervals (0–26 mbsf and 1255–1315 mbsf). The biostratigraphic data suggest an average sedimentation rate of 125 m/my from the seafloor to 1270 mbsf. Within this interval sedimentation rates vary from 45 m/my to >200 m/my. A Pleistocene condensed section and/or hiatus of ~1 my is identified.

Below 1270 mbsf, average sedimentation rates decrease and range from <1 to 4 m/my. These low average sedimentation rates may suggest the presence of several hiatuses in the Paleocene through early Miocene interval.

Paleocene sedimentation rates are distorted by the occurrence of 60 m of igneous intrusions and volcanic breccias. The oldest sediments between 1401 and 1415 mbsf are of late Maastrichtian (Late Cretaceous) age. Reworking and poor preservation make it difficult to determine whether or not the dramatic environmental changes at the Late Cretaceous/Paleocene boundary (66.0 Ma) are preserved in the recovered sediments.

Paleomagnetism

At Site U1480, we made stepwise alternating-field (AF) demagnetization measurements on all archive-half core sections. To confirm the magnetic properties observed from the section halves, discrete samples taken from working-half sections were subjected to AF and thermal demagnetization. Variations in the natural remanent magnetization (NRM) intensity generally correlate with lithology. Paleomagnetic measurements indicate that the calcareous clay and calcareous ooze in Unit I (0–26.42 mbsf) have a mean NRM intensity on the order of 3×10^{-2} A/m, whereas the fine sand with clay in Subunit IC (18.8–26.42 mbsf) has lower NRM intensity (~1×10^{-3} A/m). The NRM intensity remains quite constant (~3×10^{-2} A/m) for the silt and bioturbated clay in Unit II (26.42–1250.35 mbsf) and the grayish-green and reddish-brown clay in Unit III (1250.35–1310.02 mbsf). The NRM intensity ranges between 5×10^{-3} A/m and ~5×10^{-2} A/m for the mafic rocks and volcaniclastic sand and mud in Units IV and V, and increases to several A/m for the basaltic basement in Unit VI. Many discrete peaks of higher NRM and magnetic susceptibility values in both Units II and III can be tied directly to the presence of ferrimagnetic greigite.

As with many other ocean drilling expeditions, remagnetization imparted by the coring process is encountered at the Site U1480 holes. NRM inclinations are strongly biased toward the vertical (mostly toward +90°) in the majority of the cores. For sediment cores, AF demagnetization to 10 mT is effective in removing the drilling overprint for a high percentage of samples, as shown by a decrease in magnetization intensity and by a shift of the inclinations toward shallower values that are comparable to the inclination expected for the site (~±6°). The NRM declinations of APC cores before orientation correction differ significantly, as expected. After orientation correction using the data from the Icefield and FlexIt orientation tools, declinations become close to the magnetic north for the normal polarity cores and magnetic south for the reversed polarity, respectively, which indicates the remanence is of primary origin. The declinations and inclinations for Hole U1480E and U1480H cores are very similar for the upper ~40 m, which strongly attests to the fidelity of the paleomagnetic record and indicates a common chronology for both holes.

To construct a magnetostratigraphy for Site U1480 requires a correlation between the measured polarity pattern and the geomagnetic polarity timescale as well as using biostratigraphic constraints. At a low latitude area such as Site U1480, a near 180° shift in declination in the cores is a more reliable sign of a polarity transition than a change in inclination sign. Based on the declination data, the Brunhes/Matuyama Chron boundary (0.78 Ma) is placed at ~18.5 mbsf, and the sediments between 28 and 31 mbsf may represent the Jaramillo Subchron (0.988–1.072 Ma). The position of other chron boundaries deeper in the hole will require postcruise work.

Geochemistry

A total of 157 whole-round (WR) samples were collected from the holes drilled at Site U1480. In addition, high-resolution rhizon water samples were obtained between 74 and 99 mbsf in Hole U1480H. Geochemical profiles of the dissolved constituents in the pore fluids reflect the combined effects of organic matter diagenesis, alteration of volcanogenic sediments, and reactions in oceanic basement.

In the upper 200 m, chemical data reveal organic matter remineralization, with the depth of the sulfate-methane transition zone (SMTZ) at ~120 mbsf. Within this zone, there is an increase in alkalinity, phosphate, and ammonium over seawater values, as expected from organic matter diagenesis. However, we also observe maxima in phosphate at 20 mbsf and at 100–120 mbsf, which may reflect regional fluid transport. In the upper 200 m, there is also ample evidence for alteration of volcanic ash, and associated smectite formation, as indicated by changes in dissolved silica and potassium. The K and Si profiles also suggest zeolite formation between 300 and 450 mbsf, consistent with the presence of zeolite in the cored sediment. Deeper in the sediment section, an increase in chloride, strontium, and calcium and a decrease in magnesium indicate a contribution from basement fluid. Superimposed on these trends, there is a notable decrease in dissolved calcium and strontium between ~800 and 1200 mbsf, consistent with carbonate cementation observed in the cores.

Headspace gas analyses show that methane concentrations are generally low and changes in methane concentration and the methane/ethane ratio align with lithologic unit boundaries. Detectable methane concentrations are observed from just below the sulfate-methane transition zone (SMTZ) to the base of Subunit IIA, which may reflect the slightly lower organic C contents in Subunit IIB. Methane levels increase again and ethane becomes detectable in Subunit IIC, which may represent the onset of thermogenic methane production. Samples from Unit III show a slight decrease in methane as well as a decrease in the methane to ethane ratio. Methane concentrations drop significantly in Units IV and V, where volcaniclastic sediments and igneous rocks are prevalent.

Total organic carbon and carbonate contents are elevated in Unit I, reaching maxima of 1.8 wt% TOC and 40% carbonate in the nannofossil ooze layers of Unit I. Carbonate content is low through Subunits IIA–IIB with minor peaks at 475.1 and 698.3 mbsf and near the Subunit IIB/IIC boundary at 786 mbsf. Carbonate content reaches a maximum of 94% at 1315 mbsf, within the carbonate oozes of Unit III. Organic C to total N ratios show a distinct signature of terrigenous input in the sediments of Unit I, but remain within the range characteristic of marine organic matter below 200 mbsf. Continued input of terrestrial organic material is apparent from the strong positive correlation between C/N ratios and organic C content. The strength of the correlation increases with sample depth, consistent with continued, minor input of terrigenous organic material below Unit I.

Physical Properties

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). Discrete *P*-wave velocity and moisture and density (MAD) were measured on working-half sections. Undrained shear strength was measured in the top 370 m using the automated shear vane and pocket penetrometer. Thermal conductivities were measured on WR core sections (soft sediment) and pieces from working-half sections (hard rock). For most lithologic unit boundaries, we see general shifts in physical properties; however, there are some natural gamma ray and velocity excursions that occur within lithologic units.

NGR values are generally low in lithologic Unit I, with significant variability between 24 and 89 counts/s. Within lithologic Units II and III, NGR values are relatively constant. NGR values then sharply decrease near the base of lithologic Unit III. NGR is generally low in Units IV–VI where igneous sediments and rocks are present, although higher NGR values occur where clay-rich pelagic sediment is present in lithologic Unit V.

Porosity values determined from MAD analyses generally decrease with depth. Near-seafloor porosity is ~80% and values decrease rapidly to mean values of ~46% at 100 mbsf, and then decrease more slowly to ~31% at 1320 mbsf. The porosity values calculated below ~1300 mbsf deviate from the overall consolidation trend, with subsets of both higher and lower porosities. MAD bulk density values generally increase with depth. Bulk density is <1.5 g/cm^3 at the seafloor and increases rapidly until 30 mbsf, followed by a slower increase to values of ~2.2 at 1320 mbsf. The most striking changes in physical properties between 1305 and 1361 mbsf where porosity and bulk density show both high and low values, grain density is low, and velocity is high. The cause of these changes is not evident but may result from lithologic heterogeneity (tuffaceous, biosiliceous and calcareous rocks), mineralogical reactions that may have expelled fluid, or migration of fluid into this interval.

To complement WRMSL *P*-wave velocity measurements, over 3000 discrete velocity measurements were made on cores and core samples, providing a comprehensive compressional-wave dataset. *P*-wave velocity values show a gradually increasing trend with depth and distinct increases below 1300 mbsf. A few intervals show distinct increases in *P*-wave velocity including a ~500 m/s increase at ~1250 mbsf and marked increases within the igneous rocks where velocities exceed 5000 m/s. Generally, the *x*- and *y*-direction *P*-wave velocities are higher than the *z*-direction values with velocity anisotropy values averaging ~10%.

Magnetic susceptibility (MS) shows a distinct shift to higher values at the Unit I/II boundary with a decrease at ~1250 mbsf at the Unit II/III boundary. Within Unit II, MS values decrease slightly with increasing depth. MS has relatively low values in the sands and clays in the upper and middle portions of Hole U1480G, reaches its lowest values in calcareous sediments, and increases to its highest values in the volcaniclastic sediments and igneous rocks at the base of the hole.

In general, thermal conductivity values increase slightly with depth, from ~1.0 to ~2.3 W/(m·K). Thermal conductivity values range from 0.2 to 1.6 W/(m·K) in the sands and clays, from 1.0 to 5.5 W/(m·K) in the pelagic sediments, and from 0.5 to 3.0 W/(m·K) in the volcaniclastic sediments near the base of the hole.

Downhole Measurements

The downhole measurements originally scheduled at Site U1480 included formation temperature measurements with the APCT-3 and T2P tools, formation pressure measurements with the T2P tools, and a complete suite of logging tools. Because of tool failure during the deployment of the T2P and unstable conditions in the two holes planned for logging, the downhole measurements made at Site U1480 consisted of 11 successful formation temperature measurements with the APCT-3 to a depth of ~210 mbsf and a reduced set of logs through the casing and in 52 m of open hole below casing in Hole U1480G. The 11 formation temperature measurements define a linear temperature profile with a gradient of 44.4°C/km. Combined with an average of the thermal conductivity values measured on cores, the vertical conductive heat flow is 75 mW/m^2, which is in agreement with the broad range of values in the area.

Because of unstable borehole conditions in Hole U1480G, we deployed a shortened (19 m long) tool string made of a spectral gamma ray and a resistivity tool. The tools were unable to go deeper than ~809 mbsf (~52 m below the casing). Within the casing, the gamma ray data display little variability due to the dampening effect of the casing. In the open hole below casing, the gamma ray data show a general increase from ~50 to ~90 API. The separation of the different depth of investigation resistivity logs suggests that the hole was enlarged, which is consistent with the unstable hole in this interval.

Core-Log-Seismic Integration

The two main integration activities carried out at Site U1480 were correlation of depths between the different holes, and linking core observations to the site survey seismic data. Since logging was limited due to the instability of the hole, alternate strategies were used.

A good correlation of the cores between Holes U1480A–U1480E and U1480H has been established and a composite depth scale has been developed. The correlation is primarily based on NGR and MS measurements, but is also consistent with WRMSL *P*-wave velocity and GRA density, and color reflectance values (L*, a*, b*) measured on split cores. Since Holes U1480A–U1480D did not recover the mudline, this correlation was necessary to determine the relative and absolute positions of the cores. The comparison between Holes U1480E and U1480H from the seafloor down to 30 mbsf shows that while each has >100% recovery, there are gaps in the material sampled between cores. This composite depth scale will permit future sampling at higher resolution. Below 30 mbsf the physical properties records from the holes are consistent, but the construction of a detailed composite section is not possible.

Linking between the cores (recovered in depth) and the site survey seismic data (recorded in time) requires a time-depth relationship. It became apparent during drilling that the *P*-wave velocities obtained from the cores would not be sufficient to independently develop this relationship, and planned sonic logs and a vertical seismic profile were not obtained due to unstable hole conditions. However, variations from core observations and measured velocities did provide estimates of the positions of distinctive features for correlation with the seismic data. These were used to create a series of tie points, including two initial reference depths provided by the seafloor and acoustic basement and an additional control point that used a continuous record of drilling parameters to establish the depth of a large-scale channel prominent on the seismic profile. Overall, this correlation between core properties and seismic data provided a solid framework to tie core and seismic data.