IODP Expedition 362: Sumatra Seismogenic Zone
Site U1481 Summary

Background and Objectives

Site U1481 (proposed Site SUMA-12A) is located on the Indian oceanic plate, east of the Ninetyeast Ridge and west of the North Sumatran subduction margin and 35 km southeast of Site U1480. The primary drilling objectives at Site U1481 were to core the deeper interval of the subduction input sedimentary section and basement, to determine if the lower Nicobar fan, pelagic section, and basement at Site U1480 are representative of this part of the Indian plate, and to understand the degree of heterogeneity of sediment and basement over short distances. Drilling down without coring and installing a reentry/casing system minimized the duration of open-hole operations and thus offered an increased chance of successful wireline logging and deep coring. Based on seismic interpretations, the sedimentary section at Site U1481 is similar to that at Site U1480, and includes: a thin distal trench wedge section underlain by an unconformity (Seismic Horizon A); the Nicobar submarine fan sequence composed of an upper reflective section and a deeper less reflective section separated by Seismic Horizon B; the pre-fan sequence, which is predicted to be separated from the primary Nicobar fan sediments by Seismic Horizon C; and acoustic basement (Seismic Horizon D marks its top). Seismic Horizon C was previously identified as a potential horizon for localization of the décollement at the subduction zone. The deeper part of the stratigraphic section at Site U1481 was targeted for coring and logging because it includes many of the potential horizons that may evolve into the plate boundary décollement in the shallow and deep subduction zone, and includes sedimentary and basement materials that may be sources of fluids that may influence fault slip behavior. Cores and logs at Site U1481 provide constraints on the initial lithological, physical, chemical, and mechanical properties, and potentially the state of stress of the lower part of the input section where the plate boundary fault develops. The sedimentary section thickens significantly on approaching the subduction zone, therefore postexpedition experimental and numerical modeling work will be used at this site, as at Site U1480, to constrain the impact of increasing burial, temperature, fluid interactions, and diagenetic alteration. Site U1481 will therefore allow us to address the three expedition primary objectives to determine how the properties of the input section may lead to shallow seismogenic slip and to unusual forearc development as related to the basal properties of the prism. Site U1481 also offers the opportunity to test local variations in pre- and early Nicobar fan deposition through comparison with Site U1480.

Specific objectives were:

- To establish the onset of Nicobar fan deposition and determine the primary sources of sediment delivered to the site during early fan history.
- 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 effects of burial rate and burial 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.
- To identify fluid sources and changes with depth.
- To determine the composition and origin of basement at the site and its effect on overlying sediments.
- To compare the lithostratigraphy, geochemistry, and physical/mechanical properties with those at Site U1480 to establish local variations of the stratigraphic succession.

Operations

The 19.3 nmi transit from Site U1480 was completed in 2.4 h at an average speed of 8.0 kt. The vessel arrived at Site U1481 (proposed site SUMA-12A) at 0436 h on 8 September 2016. Operations started with the installation of a reentry system. First, we assembled 730.5 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, the drilling assembly and ~659 m of 5 inch drill pipe were connected to the Hydraulic Release Tool (HRT), and the HRT was bolted onto the casing in the moonpool. Finally, the entire reentry system and drilling assembly were lowered to the seafloor, and a free-fall funnel (FFF) was assembled in the moonpool and dropped to land on the reentry system. The subsea camera was deployed so we could confirm the FFF had seated correctly and observe the reentry system while it was drilled into the seafloor. Hole U1481A was spudded at 1500 h on 9 September, and drilling continued until the reentry system landed on the seafloor at 1910 h on 10 September. Water depth was determined to be 4190 m below rig floor (mbrf) or 4178 m below sea level. The depth of the hole was calculated at 734.1 m below seafloor (mbsf), with the end of casing at 730.5 mbsf. The drilling assembly was released from the reentry system using the HRT, and the subsea camera was recovered.

While pulling the drill string to the surface early on 11 September 2016, with the bit at ~3819 m below sea level, smoke and noise were discovered coming from the aft drawworks Elmagco (eddy current) brake. The brake was decoupled so the rest of the drill string could be pulled to the surface. After assessing the damage to the brake, it became clear that repairs would have to be made on shore. The *JOIDES Resolution* left Site U1481 at 2030 h on 11 September for Singapore. The 996 nmi transit was completed in 83.4 h at an average speed of 11.9 kt. The vessel arrived at the Loyang Offshore Terminal at 1106 h on 15 September, and the failed brake was sent to the repair facility soon after arrival. The replacement brake was delivered to the vessel at 2100 h on 15 September, the installation was completed on 16 September, and the brake was aligned and tested on 17 September. The vessel departed Singapore at 1206 h on 18 September, and the 989 nmi transit back to Site U1481 was completed in 93.1 h at an average speed of 10.6 kt.

The *JOIDES Resolution* arrived back at Site U1481 at 1100 h on 22 September, and drilling operations resumed. Hole U1481A was reentered at 0150 h on 23 September with a rotary core barrel (RCB) bottom-hole assembly (BHA). After clearing ~178 m of fill from within and just below the casing, we drilled without coring from 734.1 to 1149.7 mbsf. RCB coring started on 25 September and Cores 2R–38R advanced from 1149.7 to 1500.0 mbsf, with 219.8 m recovered. Downhole logging preparations started on 30 September. The drill bit was released at the bottom of the hole at 2315 h and the hole was displaced with 350 barrels of heavy mud. Because of hole instability, the decision was made to run a single, modified logging string composed of the magnetic susceptibility sonde (MSS), High-Resolution Laterolog Array (HRLA), Dipole Sonic Imager (DSI), Hostile Environment Litho-Density Sonde (HLDS; for caliper measurements only, with no source), and the Hostile Environment Natural Gamma Ray Sonde (HNGS) tools. Logging data were collected from 1494 mbsf (6 m from the bottom of the hole) to the seafloor, and logging activities were completed by 2100 h on 1 October. The drill string was raised to the surface and the rig floor was secured for transit. The thrusters and hydrophones were retracted at 0830 h on 2 October and the vessel departed Site U1481. The total time spent at Site U1481 was 13.2 d. Upon departure, a magnetic profile was collected between Sites U1481 and U1480. At the conclusion of the survey, the *JOIDES Resolution* resumed the 1039 nmi transit to Singapore with an estimated arrival time of 0930 h on 6 October 2016.

Principal Results

Sedimentology and Petrology

Site U1481 was drilled to investigate local variations of the lower part of the Nicobar fan and underlying pelagic sediments and basement. Sediment and sedimentary rock were recovered from 1149.7 to 1500 mbsf in Hole U1481A. Overall, the succession at Site U1481 consists of siliciclastic sediments interpreted as the lower part of the Nicobar Fan and intercalated pelagic sediments in the deepest section. Due to time constraints, coring into the deepest pre-fan pelagic sediments and basement was not possible. The sediment represents the early to late Miocene deep-marine sedimentary cover between the Ninetyeast Ridge and the Sumatra (Sunda) subduction zone. Site U1481 is located ~35 km to the southeast of Site U1480.

Two major lithologic units were identified (Units II and III) and are correlated to those observed at Site U1480. Unit II (1149.70–1360.12 mbsf) is composed of bioturbated black and dark gray clay/claystone and silty clay/claystone, and structureless muddy sand/sandstone with plant material and mud clasts. Unit II sediments are mostly unlithified but localized lithified materials were encountered (carbonate-cemented sandstone and mudstone). The base of Unit II marks a transition into sediments that are lithified. Unit II is equivalent to Subunit IIC at Site U1480. Unit III contains foraminifer-bearing, gray-green and minor reddish-brown claystone (1360.12–1498.72 mbsf) with agglutinated foraminifers. Unit III is equivalent to Subunit IIIA at Site U1480. Two notable differences with Site U1480 are that the lower part of Unit III (~1400–1498.72 mbsf) contains more tuffaceous material than at Site U1480 Unit IIIA, and there are intercalated sandstones present, which were absent in the deeper succession at Site U1480.

Structural Geology

The recovered section at Site U1481 is generally undeformed without any evidence of deformation associated with the fault zones identified on seismic reflection data as close as ~3 km from Site U1481. Bedding dips are subhorizontal throughout the cored section, and the rare faults that were discovered, especially in Unit III around 1460 mbsf, cannot be confidently interpreted as natural, tectonic structures. Some faults may be natural faults overprinted by drilling deformation. Synsedimentary deformation structures associated with slumping, such as microfaults and folds, are common in Unit II and present in Unit III.

Drilling disturbance is concentrated below 1325 mbsf. Above that depth, sections with undisturbed core are common; where the core is affected by drilling, biscuits form with only moderate intensity.

Below 1325 mbsf, severe deformation by fractures, biscuits, and breccias is common. Within drilling biscuits that are up to 50–80 cm long, many fractures developed that created core segments. Fractures developed over time after the core was split, and in intervals between the most fractured core, cores lengthened (up to 2% expansion). Fracturing and core expansion appear to reflect core unloading, and this process is limited to Unit III.

Biostratigraphy

Planktonic foraminifers only are observed in the upper 60 m of the 350 m cored interval, and in a single sample at 1280.65 mbsf (Sample U1481A-15R-CC); the rest of the section is barren. Diatoms and radiolarians occurred in two intervals, 1370–1411 and 1496–1497 mbsf. Rare calcareous nannofossils occurred discontinuously in a few samples in all three of the above intervals. The few available age-indicative species were used to establish sediment accumulation rates. The tie points used result in sediment accumulation rates that fit all biostratigraphic data except for the occurrence of the planktonic foraminifer *G. plesiotumida* at 1280.65 mbsf. The uppermost tie point is provided by a calcareous nannofossil assemblage, the middle tie point by a radiolarian assemblage, and the deepest tie point by a combination of radiolarian and diatom assemblages. These data allow us to interpret changes in sediment accumulation rate corresponding to the onset of significant Nicobar Fan sedimentation in the Miocene.

Paleomagnetism

Shipboard paleomagnetic studies for Site U1481 consisted of continuous measurements of archive-half core sections and progressive demagnetization measurements of discrete samples from working-half sections. Within the recovered rocks, there are considerable variations in magnetic properties and demagnetization behavior among the various lithologies. The intensities of natural remanent magnetization (NRM) of the archive halves span more than two orders of magnitude. Variations of magnetic properties between different lithologies are similar to those observed at Site U1480. Overall, sediments in Unit II (1149.7–1360.1 mbsf) have relatively high NRM intensity (averaging ~21 mA/m) compared to those of the gray-green and minor reddish-brown claystone in Unit III (1360.1–1498.7 mbsf) with an average NRM intensity value of ~5 mA/m. In the lower part of Unit III (~1400.0–1498.7 mbsf), NRM shows a stepwise increase, from ~2.5 mA/m (at 1400 m mbsf) to ~5.0 mA/m (at the bottom of the hole, 1498.7 mbsf), potentially resulting from a change in depositional environment and perhaps associated with the reddish-brown silty claystone and fine- to very fine-grained sandstone in these depth intervals. Variations in magnetic susceptibility are consistent with the variations in NRM intensity. Inclinations from discrete samples are mostly

concentrated at ±15° suggesting that these samples record an inclination close to the theoretically predicted value for the latitude of this site in the late Miocene, and indicating they may represent the primary remanent magnetization.

Geochemistry

The geochemical composition of fluids in the deeper sediment section of Site U1481 provides a contrasting view to the data from Site U1480 and will help us evaluate how fluid-rock interactions between these two sites may relate to variations in stratigraphy, lithology, and physical properties. These variations in turn affect the state and geomechanical properties of the input sediments before and after subduction. We analyzed a total of 32 interstitial water (IW) samples, at a frequency of one to two samples per core from Cores U1481A-2R to 38R (1149.7 to 1498.7 mbsf). Similar to Site U1480, we observed pore fluid freshening in Unit III. While there are similarities in the dehydration reactions that may lead to fluid freshening at depth, the differences in sediment composition of lithologic Unit III at Site U1481 and Subunit IIIA at Site U1480 are reflected by a lack of a pronounced increase in Si at Site U1481. Basement was not reached at Site U1481, and thus we do not have a clear indication of the effect that diffusion of ions from (or into) the basement aquifer may have on the pore fluid geochemistry at depth at this site. Relative to Site U1480, at Site U1481 calcium is relatively constant, magnesium is depleted to a lesser degree, and there is no indication of sulfate contribution from the basement.

Organic geochemistry results are similar to those from Site U1480. Headspace samples taken to monitor hydrocarbon contents showed methane levels between 144 and 4503 ppmv, well below the limits designated by the safety policy. Ethane and propane were also detected though at much lower concentrations, and the methane/ethane ratio suggests hydrocarbon production remains primarily biogenic. Total carbon (C) and carbonate concentrations are generally low at Site U1481, similar to the corresponding units of Site U1480. Organic C concentrations are also generally similar to those at Site U1480, but several elevated organic C values appear to reflect strong and localized input of terrigenous organic material based on the C/N ratios.

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, moisture and density (MAD), and thermal conductivity (TCON) measurements were made on samples from working-half sections. Trends in the physical

property data generally correlate with the lithologic units. NGR values are generally low, and vary from 46–96 counts/s in lithologic Unit II. NGR has slightly reduced variability in lithologic Unit III where values typically vary between 53 and 91 counts/s. MAD porosity values generally decrease with depth, however variations are observed within Unit III: porosity increases to 30% at 1386–1423 mbsf and decreases to ~25% below 1423 mbsf. The average grain density is 2.76 g/cm^3. MS values downhole show a distinct decrease at the Unit II/III boundary (~1360 mbsf).

P-wave velocity values show a gradually increasing trend with depth with a distinct ~600 m/s increase at ~1360 mbsf. Generally, the *x*- and *y*-direction values are higher than the *z*-direction values indicating anisotropy. Thermal conductivity values are similar in Units II and III, with a range of 1.5 to 4.5 W/(m·K) and an average of 2.46 W/(m·K). The highest values are observed across the Unit II/III boundary.

Downhole Measurements

Because of the concern that the hole would not stay open long enough to conduct multiple logging runs, we decided to deploy a single logging tool string. A modified triple combo tool string was made up with the MSS (magnetic susceptibility), HRLA (resistivity), DSI (sonic), HLDS (caliper only), and the HNGS (spectral gamma ray). The maximum depth reached by the tools was 1494 mbsf, 6 m above the bottom of the hole, indicating that only a minimal amount of fill had accumulated. The caliper log shows that the hole was in very good condition below 1345 mbsf, the interval with the most complete core recovery. Above 1345 mbsf, the hole size is irregular but does not seem to have affected significantly the quality of the data except for the sonic shear velocity waveforms. Most data agree well with the shipboard physical properties and will allow us to characterize the lithology where recovery was incomplete.

Preliminary interpretation shows that the most significant change in the data recorded occurs at 1360 mbsf, the transition between lithologic Units II and III. Below this boundary, all logs become much less variable as the formation is dominated by claystone. Logging data recorded in the drilled interval below the casing (without core recovery; 734–1150 mbsf) display a character similar to the data recorded within the cored interval of lithologic Unit II (1150–1360 mbsf), suggesting a similar lithology. The alternation of clay/claystone and sand/sandstone intervals in this unit likely controls the overall variability in the logs and the hole size.

Core-Log-Seismic Integration

Linking core observations to site survey seismic data using downhole logging data at Site U1481 was achieved by generating synthetic seismograms using the *P*-wave sonic log and linking data from a known depth to time on the seismic reflection section. Linking core data (recovered in depth) to the site survey seismic data (recorded in time) requires a time-depth relationship to be established. The *P*-wave sonic log provides seismic velocity from which a good time-depth relationship could be obtained in the uncased interval. The method focused on correlation between the cores, logs, and seismic interpretation around seismic Horizon C, and then refinement of tie points using synthetic seismograms, constructed by merging the highest quality sonic log data from the downhole and uphole logging passes. A visual correlation was then carried out against the seismic section by varying the tie time between the two datasets. A high-quality tie point was obtained between the seismic data and synthetic seismograms at Horizon C. The synthetic seismograms give an excellent fit to reflections throughout the seismic section. This tie and the successful logging suite provides excellent potential for correlation between features from the cores and the regional seismic reflection lines, as well as between reflections and petrophysical/petrological parameters estimated from the log data.