IODP Expedition 334: Costa Rica Seismogenesis Project (CRISP)

Site U1378 Summary

Background and Objectives

Site U1378 was drilled into the middle slope of the Costa Rica margin, 41 km offshore Osa Peninsula and Caño Island along BGR99 Line 7. It is located above the unlocked portion of the plate boundary according to interplate earthquake relocation and geodetic measurements (Bilek, 2003; LaFemina et al., 2009). The margin here consists of an upper plate basement underlying about 750 m thick slope sediments. The seismic sections show that this site is located above the seaward edge of one of the high amplitude reflectors interpreted as displacement surfaces, which Site U1378 was designed to penetrate. The primary purpose of drilling Site U1378 was to determine the nature, composition and physical properties of the upper plate basement and to understand the nature of the landward dipping seismic reflectors. Additional objectives included (1) determination of the stress and strain regime of the unlocked portion of the margin (2) reconstruction of the stratigraphy of the slope sediments and documentation of the margin subsidence/uplift, (3) understanding of the fluid-flow regime above the high amplitude reflector interpreted as a fault, (4) calibration of the BSR derived temperature, (5) and estimation of the quantity of tectonically eroded upper plate material.

The seismic interpretation of Site U1378 is based on the pre-stack depth migrated section BGR99 Line 7 processed by C.R. Ranero. The site is located at CMP 2500 (lat. 8º 35.5414’ N, long. 84º 4.6306’ W), at a water depth of 527 m. The seismic stratigraphy of the sedimentary slope at Site U1378 shows a good continuity of reflection events. The upper 100 m of the slope sediment sequence shows rather clear horizontal reflections. The next 100 m of sediments below form the weakest reflective part of the sequence. From there it grades downward in a more highly reflective zone that is basically continuous between 500-600 mbsf. The reflectors in this interval are gently dipping seaward, and the sequence is clearly cut upslope (toward the NE) by a younger sequence forming an angular unconformity. The bottom part of the sedimentary sequence is sharply marked by a high amplitude reflector that is interpreted as the top of the upper plate basement. The velocity in the basement increases from <2m/s in the sediments to 2.8 m/s in the fault zone to >3.3 m/s. The surface marking the basement top is irregular and several landward high amplitude reflectors that were interpreted as faults cut it. The basement top is displaced a few tens of meters across these faults. In the vicinity of Site U1378 the slope sediments are not deformed by the faults, but they get thicker in correspondence to the fault cutting the basement reflector, indicating a normal movement along the faults themselves. Some growing strata visible along BGR99 Line 7 also confirm this normal sense of displacement.

At Site U1378, the temperature at the plate boundary was interpreted to be at least 140°C (Grevemeyer et al., 2004). Recent new modeling of the intraplate temperature lowers the temperature to between 60°C and 90°C (Harris et al., 2010). Visual observations and the towed ocean bottom instrument (TOBI) detected abundant mud mounds and vent communities within few kilometers from the site (McAdoo et al., 1996; Weinrebe et al., 2003). Many of these structures seem to be related to active faults (Hensen et al., 2004; Ranero et al., 2008). Judging from the continuity of the landward dipping reflectors interpreted as faults, any fluid advection along these structures will originate in areas of at least 4 km depth.

Scientific Results

Two holes were drilled at Site U1378 penetrating 456.9 m and 523.9 m below the seafloor, respectively. Hole U1378A was dedicated to logging while drilling operations to measure the in-situ physical properties of the material in the borehole. Hole U1378B was designed to retrieve as much core of the sediment coverage and the basement as possible within the specified time window. Overall 526.39 m of sediment have been retrieved with an average total recovery rate of 100.5%. The basement has not been reached in any of the holes because drilling had to be terminated early due to unfavorable hole conditions.

Based on lithological characteristics the sediments recovered at Site U1378B can be divided, into two main lithostratigraphic units: Unit I, about 128 m thick, is composed of mainly soft, dark greenish gray, terrigenous silty clay. Intercalated in this silty clay is a series of about ≤ 5 cm thick fining upward sequences consisting of lithic sands and 21 tephra layers, ranging in thickness from 0.5 to 7 cm. The basal boundary between the silty clay and the sand and tephra sequences are sharp, whereas the top boundaries are gradational. Unit II, being about 385.73 m thick, consist predominately of massive, well consolidated, olive green, terrigeneous clayey silt(stone) and silty clay(stone) with minor layers of sand(stone), sandy silty clay(stone), clay, clayey silt(stone), and tephra (61 layers) that remain unlithified down to a depth of 560 mbsf. The basalt contact between the background sedimentation and the tephra layers is again sharp, whereas the top contact is gradational. Within this monotonous sequence, sandy intervals become thicker and more common with depth. Throughout the entirety of Unit II fining- and coarsening-upward dm-scale sequences of sands are present. In the coarser sand layers rip-up clasts, rounded clay lenses and abundant shell fragments, are commonly observed. Framboidal pyrite was observed macroscopically and in many of the smear slides throughout Unit II.

In contrast to Hole U1379C, horizons of abundant calcareous concretions or lithified carbonate mud clasts are rare and concentrated within a 2 m interval (Sections 27X-4, to 27X-CC, 222.08–224.41 mbsf).

The 82 identified tephra layers seem to be quite heterogeneous in composition. Thirty of them are light gray to pinkish/brownish white felsic tephras, 40 are pinkish gray/brown more mafic tephras and 12 are pinkish/greenish black mafic tephras. Mafic tephra beds account for ~15% of the total tephra-bed assemblage in Hole U1378B. The felsic tephra layers are mainly (>90 vol.%) composed of fresh, clear, colorless, fine to coarse ash sized glass shards varying from angular blocky, cuspate, flat and Y-shaped shards with nearly no bubbles to highly vesicular, pumiceous textures with many elongated bubbles. Dark gray, mafic ash layers consist predominantly of dark to light brown glass shards. Most of the glass shards have blocky shapes and are medium to poorly vesicular and show strong signs of alteration, especially in the deeper part of the hole.

Generally, the sediment cored in Hole U1378B is characterized by low-angle bedding planes (less than 30˚) as well as by healed and open faults with relatively high dipping angles. Sediment-filled-vein structures were observed from 262.2 mbsf on downwards. The main fault populations, characterized by zones of intense brecciation and sediment deformation, occurred below a depth of 200 mbsf, at the following depth intervals: (1) 279.2-281.4 mbsf, (2) 361.9-376.5 mbsf, (3) 475.9-477.2 mbsf, and (4) 514.2 mbsf - unknown lower boundary. Hence, the fault zones occur at shallower depth compared to those in Hole U1379C. The second fault zone shows the most intensive deformation and corresponds to a small density and high porosity interval identified by LWD.

Similar to Hole U1379C, the preliminary XRD analysis of the sediment suggests that there is little variation in composition among the different lithostratigraphic units. The XRD data indicate that the major mineral components are clay minerals including illite, smectite, kaolinite, attapulgite, as well as calcite, anorthite and quartz. Amphibole (hornblende, richterite), chlorite, pyroxene (augite, hypersthen), olivine, and pyrite peaks are of minor abundance.

The physical property data obtained on the cored material display an expected behavior with depth and reflect the different units cored. Physical property measurements were made after sediment cores reached thermal equilibrium with ambient temperature at approximately 20°C. Values of the wet bulk density increase with depth likely due to dewatering caused by over burden pressure and are well described by a linear trend. A small offset in wet bulk density values marks the boundary between lithostratigraphic Units I and II. Grain densities are relatively constant with depth with an average value of 2.69 g/cm^3, however, they are quite variable in Unit II ranging between approximately

2.5 g/cm^3 and 2.9 g/cm^3. There is no discernable offset between values characterizing lithostratigraphic Units I and II. On the whole, these values suggest a terrigenous origin. Porosity, being inversely correlated with bulk density, decreases from approximately 70% at the seafloor to 40% at the bottom of the hole. A slight increase in porosity between Units I and II corresponds to the decrease in wet bulk density at this boundary. An increase of porosity is observed at ~440 mbsf and corresponds to a sandy interval. Porosity increases a few percent between approximately 480 and 529 mbsf and may correspond to a decrease in the clay content. Magnetic susceptibility in the sedimentary sequence is low indicating an abundance of non-iron bearing clays. However a region of generally higher values lies between approximately 85 and 195 mbsf. Other notable regions of relatively high values occur at 335, 355, 440, and 460 mbsf. These excursions show high wave number variability and may be due to lithologic variations between sands, silts, and clays. The natural gamma ray (NGR) shows a small positive trend through lithostratigraphic Unit I and is relatively constant through Unit II. Notable excursions to higher values in Unit II occur at approximately 200 mbsf and 480 mbsf. These lowermost NGR high is associated with scoria and a high abundance of mafic glass particles. Thermal conductivity measurements show that the thermal conductivity generally increases with depth and is inversely correlated with porosity. In the upper 100 mbsf variability is significant and likely reflects gas concentrations in the core. Down hole temperature measurements using the show a linear equilibrium temperature increase with depth; coupled with the average bottom water temperature and thermal conductivity measurements, they give a least-squares geothermal gradient of 51.4 °C/km and a heat flow of 44 mW/m2. This value is consistent with forearc values of heat flow.

Generally, the observations summarized above are consistent with changing depositional conditions in a more down-slope environment. The cover sequence recovered at Hole U1378B is a terrestrially sourced slope sequence that is consistent with high sediment accumulation rates throughout the depositional interval. Recognition of wood debris and thin layers (<5 cm thick) of normal graded sands with sharp erosional bases within Unit I at this site are consistent with deposition in the distal facies of a clastic turbidite sequence. It is worth noting that Unit I at Site U1378 is not observed at Site U1379. The clay-rich deposits of Unit II at Site 1378 are lithostratigraphically similar to those observed in Unit II at Site 1379.

This is also consistent with the results of shipboard studies of calcareous nannofossils and foraminifers. Biogenic components in the cored sediments have a bimodal distribution in Unit II. Whereas shell fragments, diatoms and nannofossils are sparse but ubiquitous throughout the unit, foraminifers are partly enriched within the sediments and are a major constituent of the sand-sized fraction of the sediment. Based on nannofossil biostratigraphy, the sediments of the basal core were most likely deposited in the lower

Pleistocene, thus the sediments throughout the core are younger than 2 Ma. The sequence between 5.36 and 224.39 mbsf is assigned to the undifferentiated Zones NN21-NN20 of the Late to Middle Pleistocene based on the presence of *Emiliania huxleyi* in Section U1378B-1H-CC (5.36 mbsf) and the absence of *Pseudoemiliania lacunose*. Good preservation allows the tentative identification of *E. huxleyi* in Sections U1378B-1H-CC (5.36 mbsf) through U1378B-16H-CC (127.91 mbsf). Sections U1378B-28X-CC (237.47 mbsf) through U1378B-63X-CC are assigned to Zone NN20 based on the last occurrence (LO) of *Pseudoemiliania lacunosa* in Sections U1378B-28X-CC (237.47 mbsf) and the absence of *Discoaster brouweri*. Section U1378B-57X-CC (476.18 mbsf) contains the first occurrence of Early Pleistocene marker *Helicosphaera sellii*. Dominant species include *Helicosphaera carterii, Gephryocapsa oceanica, G. caribbeanica,* G. small, and *Calcidiscus leptoporus*. Thus, averaged sedimentation rates are approximately 516 m/m.y. and 236 m/m.y. in the upper part (<237 mbsf) and in the lower part (237~524 mbsf), respectively. Although the boundary of planktonic foraminiferal zones was not established, a few occurrence horizons of index species are approximately concordant with nannofossil zonation.

Planktonic foraminifers, are common to rare in the upper part of Hole U1378B, and are mainly dominated by tropical fauna such as *Globigerinoides quadrilobatus (Globigerinoides sacculifer), Globigerinoides ruber, Orbulina universa, Globorotalia menardii*, and *Neogloboquadrina dutertrei*. Two index marker species of planktonic foraminifera were identified in limited horizons. Section U1379C-5H-CC (43.77 mbsf) contained pink color *Globigerinoides ruber* (last appearance age of 0.12Ma), whereas Section U1379C-4H-CC (34.62 mbsf) did not contain the pink colored specimen. Thus, marine isotope stage 5e would be located in the interval between these two samples, and the horizons are assigned to foraminiferal zone PT1. Coiling change of Pulleniatina from sinistral to dextral was observed in Sections U1378C-42X-CC (351.71 mbsf) to 30X-CC (245.19 mbsf). Thus, the sediments from Section U1378C-42X-CC are older than 0.8 Ma.

Benthic foraminifers abundantly occur in the upper part of Hole U1378B, abundances in the lower parts are common or rare. Generally, the majority of the observed benthic foraminiferal species are similar to modern assemblages that are characteristic for the oxygen minimum zone in this region. Thus, the benthic foraminiferal community observed in the sediments of this hole are dominated by bathyal species. The faunas include many species similar to those of the shallower Site U1379, but bathyal species are more abundant. In general, the upper part of cored sediments at this site contains *Pseudoparrella bradyana, Trifarina carinata, Valvulineria inflata, Cassidulina limbata*, Uvigerina, and Gyroidina. Bolivina is characteristic for the upper to middle bathyal environment. In contrast to this, the sediments of the lower part of this site (>209.28

mbsf) contain species being characteristic for a higher water depth (*Uvigerina hispida, Melonis barleeanus, Gyroidina* and *Oridorsalis umbonatus*). Generally, the faunal changes observed at this site reflect continuous environmental changes from upper slope to middle slope.

Pleistocene deposition ages of the cored sediments are also supported by magnetostratigraphic investigations of the sediments. Remanent magnetization was measured on archive half-cores and on discrete samples taken from the working half recovered from Hole U1378B. All archive half cores were demagnetized in an alternating-field (AF) to 15 mT and measured with the pass-through magnetometer, whereas discrete samples were subjected to stepwise AF demagnetization and measured in both the SRM and a JR6 magnetometer. Cores U1378B-1H through 16H were cored with the APC coring system using a non-magnetic cutting shoe and oriented with the Flexit orientation tool. Cores U1378B-17X through 63X were cored with the XCB system using a standard cutting shoe. For the APC cores, both pass-through and discrete sample measurements do not show any sign of reversed polarity of magnetization. In addition, declination data corrected by the Flexit Orientation tool do not show a near 180° shift in declinations. Thus, the sediments in the APC cored interval (128 mbsf) seem to be deposited within the Brunhes period (<0.78 Ma). This age assignment is consistent with the shipboard micropaleontological data, which suggest that the foraminifer fossil pink ruber found in Core U1378B-5H may be of 0.125 Ma in age. Paleomagnetic measurements on the XCB cores so far have not revealed any reversed polarity for sediments from Hole U1378B. Additional shore-based work is required to check or confirm the shipboard data.

The geochemical trends displayed by the analyzed pore water (82 whole rounds) and gas samples (65 headspace samples, 99 void gas samples, 173 gas samples) are consistent with the different materials cored and being present at the basement and thus with the geodynamic setting encountered at this site. The pore fluid profiles of sulfate, alkalinity, ammonium, methane and calcium in the upper 20 mbsf at this site reflect typical changes associated with organic carbon cycling. Sulfate concentrations decrease almost linearly from the seafloor to the sulfate/methane transition zone (SMTZ) at ~13 mbsf, whereas alkalinity increases from the seawater value at the seafloor to a maxima at 24 mbsf. Likewise, ammonium concentrations increase in the zone of active sulfate reduction and reach local maxima below the SMTZ at 24 mbsf, reflecting on-going organic matter diagenesis. Calcium concentrations decrease from seawater value at the seafloor in this zone, reflecting the precipitation of authigenic carbonates. The highest methane concentrations are observed just below the SMTZ between 14.1 and 23.6 mbsf. The gas at these depths result from biogenic production as indicated by the high ratio of methane to heavier homologues (ethane and propane), with $C_1/(C_2+C_3)$ values ranging from 8,000 to 15,000 ppmv. From 20.7 to 200 mbsf, the ratio mainly steadily decreases and is interpreted as a mixing zone between shallow biogenic and deep-sourced thermogenic gas transported upwards by diffusion.

From 100 to ~440 mbsf, salinity, Cl, Mg, K, B, and Na concentrations mainly show a monotonic decrease with depth. Dissolved calcium concentrations are variable to ~200 mbsf, then increase with depth to a peak concentration at 440 mbsf that is coincident with minima in Cl, Mg, and K concentrations, respectively. Silica concentrations are variable with depth, and there is a concentration maxima at 300 mbsf and a minima at 100 mbsf and 460 mbsf in the same interval as the maxima in Ca concentrations. Collectively, the pore fluid chemical profiles suggest there is a unique fluid between 420 and 500 mbsf characterized by relatively low salinity, Cl, Mg, K, alkalinity, Si, and Sr concentrations and elevated Ca concentrations. This depth interval also corresponds with a marked increase in thermogenic hydrocarbons (propane, n-butane, and iso-butane). The in situ temperature at this depth is too cold for the local generation of thermogenic hydrocarbons, suggesting lateral migration of a fluid sourced in a region with temperatures high enough to support clay dehydration and thermogenic hydrocarbon production.

The three samples recovered below 500 mbsf, show a steep depth gradient in salinity and chloride, indicating diffusional communication with another fluid below the cored section. Since the Cl and salinity profiles decrease below 500 mbsf, this fluid must be fresher than the deeper-sourced fluid sampled between 420 mbsf and 500 mbsf. Ethane, propane, iso- and normal butane all show a maxima at 518.7 mbsf. Corresponding with the increasing concentrations and maxima of these higher chain hydrocarbons (C_{2+}), the $C_1/(C_2+C_3)$ ratios indicate the dominance of thermogenic gas at depth at Site U1378.

Results from logging-while drilling (LWD) generally correspond to the observations as well as to the physical property data obtained from the cored sediments. The LWD tools deployed in the hole included the adnVISION 675 (density, neutron, ultrasonic caliper), the TeleScope 675 (MWD: power and data transmission, drilling parameters), the arcVISION 675 (propagation resistivity, gamma ray, annular pressure), and the geoVISION 675 (resistivity images, gamma ray). The measurements recorded by the LWD tools were downloaded and processed successfully, except for the geoVISION resistivity image data.

Two logging units were defined on the basis of the LWD measurements. Logging Unit 1 (0-82 mbsf) corresponds to a compacting sequence where density and resistivity increase and porosity decreases with depth, reaching values of about 1.6 g/cm^3, 1 ohm.m, and 60% porosity at the base of the unit. The top of Logging Unit 2 (82-455 mbsf) is marked by a step increase in density and resistivity, which then increase slowly with depth (from 1.8 g/cm^3 and just above 1 ohm.m at the top to 1.9 g/cm^3 and just below 2 ohm.m at the bottom of the unit). Porosity shows a matching small decrease with depth, from 55% at the top of Logging Unit 2 to 45% at the base.

The adnVISION tool collected oriented images of bulk density and borehole radius. Despite its limited azimuthal resolution (image data are sampled in 16 azimuthal sectors, i.e., every 22.5°), the images display well-defined vertical bands of large borehole radius in the interval 110-438 mbsf, interpreted as borehole breakouts caused by differences in the principal horizontal stresses. The average azimuth of the breakouts is roughly NE-SW to ENE-WSW, indicating that the maximum horizontal stress is oriented NW-SE to NNW-SSE.

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