IODP Expedition 334: Costa Rica Seismogenesis Project (CRISP)

Site U1379 Summary

Background and Objectives

Site U1379 was drilled in the upper slope of the Costa Rica margin, 28.2 km offshore Osa Peninsula and Caño Island along BGR99 Line 7. Site U1379 is located above the locked 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 slope sediments that are about 890 m thick. The primary purpose of drilling Site U1379 was to determine the nature, composition and physical properties of the upper plate basement. This site was also designed as "pilot hole" in preparation for proposed deeper CRISP Program B drilling at this location. Additional objectives included (1) determination of the stress and strain regime of the locked 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 and the role of slope sediments, and (4) estimation of the quantity of tectonically eroded upper plate material.

The seismic interpretation of Site U1379 is based on the pre-stack depth migrated section BGR99 Line 7 processed by C.R. Ranero. The site is located at CMP 750 (lat. 8º 40.8496' N, long. 84º 2.0169' W), at a water depth of 125 m. Stratification in slope sediment is coherent and the section is therefore likely to yield a complete Neogene sedimentation history. The seismic reflectors within the first 800 m of the section, in fact, show a good continuity. An angular unconformity is inferred to occur at about 550 mbsf. The upper 550 m of the slope sediment sequence is shows rather clear horizontal reflections. The lower sequence shows reflectors that are gently dipping seaward (toward the NE). 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 bottom reflectors of the slope sediments are gently dipping landward, whereas toward the NE, they abruptly terminate against the basement. One of the high amplitude reflectors in the sediment sequence also cuts through the upper plate. This is a clear evidence of normal displacement along these latter structures. The velocity in the basement increases from <2.3 m/s in the sediments to >3.6 m/s. The surface marking the basement top is, just in the area of Site U1379, rather regular and subhorizontal.

At Site U1379, the temperature at the plate boundary was interpreted to be >150°C (Grevemeyer et al., 2004). Recent new modeling of the intraplate temperature lowers the temperature to about 90°C (Harris et al., 2010). Because of its shallow water depth the high-resolution benthic paleontology at this site should provide an excellent record of vertical tectonism related to the estimation of the thickness of the subduction channel. This site overlies the seismogenic zone as defined by the aftershock sequence of the 2002 M. 6.4 Osa earthquake (Bilek, 2003; Arroyo, 2008) in an area where the plate boundary is 4.5 km below seafloor. Stress measurements here will tie offshore and onshore strain measurements and may show stress transients associated with the currently locked plate boundary offshore and beneath the Osa Peninsula.

Scientific Results

Three holes were drilled or cored at Site U1379 penetrating 960 m, 10.5 m and 949 m into the seafloor, respectively. Hole U1379A was dedicated to logging while drilling operations to measure in situ the physical properties of the material in the borehole. The hole was drilled with an 8 ½" drill bit with logging while drilling (LWD) tools in the BHA. Hole U1379B was completely dedicated to high resolution geochemical and microbiology sampling to precisely determine the depth of the sulfate to methane transition zone and the associated microbiological changes. It was drilled with the APC coring system. Hole U1379C was designed to retrieve as much core of the sediment and the basement as possible within the specified time window. It was drilled with the APC coring system to APC refusal at 91.2 mbsf, followed by the XCB coring system to a refusal depth of 949.0 mbsf. The APCT3 temperature tool was deployed 6 times and useable data were recovered 5 times. The Flexit orientation tool was deployed on all APC cores in Hole U1379C, but data were lost from the first 10 cores when a critical computer was turned off during the first tool's deployment, causing the tool to lose synchronization with the computer. All APC holes were cored with non-magnetic core barrels. Core recovery for Site U1379 was 100.3% with the APC coring, and 84.4% for the XCB coring system. Overall 804 m of sediment and 12 m of basement have been retrieved, despite the difficult drilling conditions in the basement.

Based on lithological characteristics, the sediments recovered from Hole U1379C can be divided, going from top to bottom, into five main lithostratigraphic units: Unit 1, the relatively thin top unit, consists of medium to coarse grained sand with abundant shell fragments. Unit 2, about 650 m thick, is composed of mainly olive green clayey silt(stone) and silty clay(stone) with minor layers of sand(stone), sandy silty clay(stone), clay, clayey silt(stone), and tephra. The sediments in this unit are massive and well consolidated; the tephra layers are unlithified. Superimposed on the main background sedimentation of Unit 2 are three different subunits mainly consisting of consolidated clay, of clayey silt with intercalated carbonate and dolomite concretions and of fining- and coarsening- upward dm-scale sequences of silty sands and sandstone, respectively. Unit 3 is about 229 m thick and consists of fining- and coarsening- upward sequences (dm thick) of olive green silty sands and sandstone. Smear slides indicate that the sandstones are dominated by lithic clasts composed of magmatic rock fragments and feldspar minerals. Chlorite is the most abundant accessory mineral and is followed, in the order of abundance, by volcanic glass, opaque minerals, and amphibole. Trace abundances include calcite, pyroxene, quartz, and opaque minerals. Tephra layers are of low abundance in this unit, accumulating mainly in one sequence within the upper part of the unit. Unit 4 (~2 m thick) consists of carbonate-cemented medium- to coarse-grained sand with well-rounded, lithic pebble- sized clasts and thick-walled shell shards. Unit 5 has a thickness of about 67 m and is composed of a matrix-supported breccia with clasts of limestone, basalt and mudstone in a fine sandy matrix intercalated with basalt in the upper part (881.75 – 906.72 mbsf) and a sequence of variably sandy and clayey silt in the lower part (916.40 – 947.52 mbsf). The basalt ranges from aphyric to moderately phyric, containing plagioclase, pyroxene and olivine phenocrysts and showing minor signs of alteration along veins.

Overall, 53 tephra layers (2 to 45 cm thick) have been identified intercalated in the background sedimentation of the different units, the majority of them below 324 mbsf. Intensive smear slide investigation has shown that most tephras consist of felsic glass shards varying from angular blocky, cuspate, flat and y-shaped shards with nearly no bubbles to highly vesicular, pumiceous textures with commonly elongated bubbles. The transparent glass shards of the felsic tephras are mostly fresh without any signs of alteration until Core U1379C-60X. Below this core divitrification structures increase with depth within the glass shards, reflecting differing levels of alteration. Grain size ranges from very fine to coarse ash (up to mm size). Identified mineral assemblages consist of plagioclase, pyroxene, hornblende, and biotite. Plagioclase is the dominant phase, but some tephras, are dominated by amphibole and biotite, which normally occurs in the most evolved felsic layers. The few observed dark gray mafic ash layers are predominantly composed 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. The mineral assemblages of the mafic tephras include plagioclase, pyroxene and spinel. In contrast to felsic tephras, mafic tephras contain more crystals. In general, tephra layers have a sharp basal contact to underlying terrigenous sediment but a gradual transition with overlying ash-bearing terrigeneous sediment, and many are normally graded in grain size, and well sorted.

The structural characteristics of the cored sediments can be divided into three zones corresponding to the upper and lower part of the sedimentary sequences and the basement, respectively. The upper part of the sedimentary sequences and the basement represent zones of gentle dipping bedding planes and poor fault populations. Several healed normal faults and layer-parallel faults, likely formed during early stage deformation, were found in the upper part of the sedimentary sequences (lithological Unit

II). A zone showing steep bedding dips and increased fault populations characterizes the lower part of the sedimentary sequences, below 597 mbsf. This part contains at least four fault zones composed of brecciated zones, fracture zones and weakly deformed zones. The first fault zone 642.1-652.8 mbsf) corresponds to the lowermost section of lithostratigraphic Unit II and to considerably small density and high porosity intervals identified by LWD.

Even though macroscopically these sediments seem to be quite heterogeneous, XRD analytical results indicate that there is little variation in composition across the lithological units described. XRD traces indicate that the major mineral components are calcite, anorthite and quartz, with the accessory minerals being amphibole, chlorite, pyroxene, olivine, and pyrite. Although very little monocrystalline quartz grains have been seen in the smear slides produced from these sediments, it may be possible that other silica rich components (sedimentary and magmatic lithic fragments) are producing this signal.

These findings are generally supported by physical property data obtained on the cored material. Values of bulk density were determined from both GRA measurements on whole cores and mass/volume measurements on discrete samples from the working halves of split cores. In general, values of wet-bulk density determined from whole round GRA measurements and measurements from discrete samples agree well. Generally, wet-bulk density increases with depth, increasing more rapidly in the upper section than in the lower section, likely due to dewatering caused by over burden pressure. Bulk density values in the brecciated basement are approximately 2.3 g/cm^3. Grain densities determined from discrete samples are relatively homogeneous, ranging between 2.6 and 2.8 g/cm^3. Measured porosities within the sediment section are inversely correlated with bulk density, decreasing with increasing depth. Magnetic susceptibilities are, with two exceptions, generally low and uniform, indicating an abundance of non-iron bearing clays. Basement values of magnetic susceptibility are generally greater than those in the sediment. Measured natural gamma ray values are relatively uniform down to about Core U1379C-78X below which they start to decrease being consistent with the observed downward increase of sandy sediments and the increase in grain density. NGR values in the basement are generally low consistent with the sandy lithologies described in this interval. P-wave velocities show a sharp increase going from the sediment coverage into the basement reflecting the low porosity and high consolidation of the sediments. Thermal conductivity generally increases with depth and is inversely correlated to porosity. Measured downhole temperatures using the Advanced Piston Coring Temperature tool show a relatively linear increase of equilibrium temperatures with depth. Coupling these temperatures with the average bottom water temperature as well as with the measured thermal conductivity results in a least-squares geothermal gradient of

41.6 °C/km and a heat flow of 40 mW/m^2. This value is consistent with forearc values of heat flow.

Generally, the observations summarized above are consistent with changing depositional conditions in a forearc basin that may range from a nearshore environment to shelf sediments to upper slope sediments (turbidites) interrupted by calcareous mud debris from close fluid venting areas. The calcareous microfossil community identified in the cored sediments also supports this interpretation.

Shipboard studies of calcareous nannofossils and foraminifers are generally used to further constrain the depositional environment of the cored sediments as well as their ages. Calcareous nannofossils provided an excellent biostratigraphic control for most of the cored section. All observed microfossils are characteristic for the Pleistocene. Based on the nannofossil biostratigraphy, the sediments retrieved from the lowest core seem to be deposited during the lowermost Pleistocene. Thus, the sediments throughout the core would be younger than 2.6 Ma, resulting in an average sedimentation rate for the upper part (~566 mbsf) and the middle part (566~722 mbsf) of the section of approximately 1230 m/m.y. and 100 m/m.y., respectively. Although the boundary of planktonic foraminifera could not be established, a few occurring horizons of index species are approximately concordant with nannofossil zonation. The benthic foraminifera, however, provided significant insights into the changing depositional environment of the Costa Rica convergent margin. The faunal changes reflect continuous environmental changes from continental shelf to upper slope (middle bathyal).

Pleistocene deposition ages as well as high sedimentation rates are also supported by the magnetostratygraphic investigation of the sediments. The remanent magnetization of the sediments has been obtained by pass-through magnetometer measurements on all split-core archive sections with variable measuring intervals (2–10 cm). Discrete samples were also collected from the working halves of all cores, at a spacing of one sample per section (1.5 m). In order to isolate the characteristic remanent magnetization (ChRM), the cores were subjected to alternating-field (AF) demagnetization. The half-cores were typically demagnetized up to 30 mT. In order to test the half-core data a total of 85 discrete samples were demagnetized using progressive AF demagnetization techniques and measured them in both the SRM and the JR6 magnetometer. The ChRM inclinations from discrete measurements have been used to define magnetic polarity sequences for Site U1379, although at low latitude area such as Site U1379, near 180° shift in declination in the cores would be a more reliable sign of the polarity transition. For the upper part of the Unit II, both pass-through and discrete sample measurements do not show sign of reversed polarity of ChRM. Since the orientation data by the Orientation Tool were lost, we cannot compare the declinations across APC cores (upper 94 m of the drilled sequence) to check whether there is near 180° shift in declinations. As such, we tentatively conclude that the APC cored part in Unit II is within the Brunhes Chron (<0.78 Ma).

In the lower part of Unit II, only one relative well defined polarity interval has been identified in downhole magnetostratigraphic records, which occurs at depth interval of ~701-704 mbsf. Section U1379C-83X-3 through top part of Section U1379C-83X-4 show dominantly reversed polarity after AF demagnetization. Discrete samples taken from these two sections also show negative inclination, consistent with the notion that these cores were magnetized in a reversed field. Biostratigraphic zone NN19 of the Early Pleistocene is also placed at this interval. Using calcareous nanoplankton zonal schemes for eastern equatorial Pacific for the lower boundary of NN19 (2.3 Ma), this observed reversed polarity should correlate with the Chron C1r.2r (1.185-1.778 Ma). If true, this would suggest fast sedimentation rate (>388 m/my).

The geochemical trends displayed by the analyzed pore water samples (110 whole rounds), sediment plugs (118 samples) and void gas samples (74 samples) are also consistent with the different materials cored and thus with the geodynamic setting encountered at this site. The upper 50 mbsf at this site reflect typical changes associated with organic carbon cycling. Alkalinity and ammonium increase from seawater values to maxima at 12 mbsf, reflecting organic matter diagenesis. At ~14 mbsf, the sulfate gradient decreases associated with a concomittant decrease in ammonium concentrations and decrease in the alkalinity gradient. Based on the sulfate data, the depth of the sulfate/methane transition zone (SMTZ) is estimated to be ~30 mbsf. This zone is characterized by a decrease in dissolved calcium, suggesting authigenic carbonate precipitation between 20 and 30 mbsf). Below the SMTZ, methane concentrations increase with depth and reach the highest concentrations from 42.31 to 67.18 mbsf. The methane at these depths is dominated by microbial production, as indicated by the high ratio of methane to heavier homologues (ethane and propane), with $C_1/(C_2+C_3)$ values about 8,000 to 10,000.

The pore fluid geochemistry below the zone of most intense biogeochemical cycling can be split into three zones. The first zone extends from ~50 to 500 mbsf and is characterized by a steady increase in Ca concentrations and a decrease in Mg and K concentrations with depth. These trends are most likely not the result of volcanic ash alteration to clays and zeolites, because salinities (hence Cl) decrease with depth rather than increase as would be expected and the tephras recovered are largely unaltered. The trends rather appear to result from clay-ion exchange, ongoing biogeochemical reactions, and authigenic carbonate precipitation/ dissolution reactions. Below ~100 mbsf, ethane concentrations increase progressively whereas propane to pentane are only detected in insignificant amounts. At ~360 mbsf, abrupt increases in C_2 to C_5 gas concentrations correlate with an increase in ammonium concentrations observed in the pore fluids. Another peak in the heavier hydrocarbon gases occurs at 440 mbsf, and both C_2 to C_5 maxima indicate the presence of thermogenic gases at and below 360 mbsf.

The second zone occurs between ~500 and 800 mbsf and is characterized by a broad zone of low Ca, salinity, Mg, ammonium and alkalinity concentrations. The K concentration-depth profile, however, shows a steady decrease in this interval, which is similar to the gradient observed in the upper 500 m of the sediment section. The lowest $C_1/(C_2+C_3)$ values observed at this site occur in the zone between 598.49 and 656.55 mbsf, in which methane concentrations are between ~ 3,000 to 6,000 ppmv. A strong peak in C_3-C_5 concentrations occurs at ~650 mbsf and is coincident with the minima in Ca and salinity concentrations observed in the pore fluids. The broad decrease in the major elements and decrease in the ratio of methane to the heavier hydrocarbons correlates with lithologic Unit III which is dominated by coarser-grained sediments, as well as several fault zones identified below ~600 mbsf. Generally, the inorganic and organic geochemical data suggests lateral and upward flow of a low salinity (hence Cl) fluid with elevated concentrations of thermogenic hydrocarbons (up to isopentanes) and potassium. The geothermal gradient at Site U1379 is 40ºC/km, thus the temperature between 600 and 800 mbsf ranges from 24-32ºC. This temperature range is too low for the in situ production of thermogenic hydrocarbons or for extensive clay dehydration, suggesting the fluid sampled in Unit III is from a deeper source and is migrating laterally and upward along the permeable sand horizons and faults.

The third zone occurs from ~800 to ~900 mbsf (Unit III into Unit IV) and is characterized by a strong linear increase in Ca concentrations and a decrease in Mg concentrations. These trends suggest that the basement fluid is dominated by fluid rock reaction with basalt in the basement.

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 data. The Schlumberger logging engineers and an Schlumberger LWD data processing center in Houston were unable to recover useful geoVISION measurements.

Based on the LWD measurements four logging units have been defined. Logging Unit 1 (0-492 mbsf) corresponds to a compacting sequence where density and resistivity increase and porosity decreases with depth, reaching nearly constant values of about 1.9 g/cm^3, 1 ohm.m, and 45% porosity at the base of the unit. The top of logging Unit 2 (492-600 mbsf) is marked by a small step increase in density and resistivity (about 2 g/cm^3 and 1.3 ohm.m). The distinguishing feature of Logging Unit 3 (600-892 mbsf) is the presence of many borehole enlargements, which are likely to correspond to intervals containing unconsolidated sands or fractured intervals. Logging Unit 4 (892-955 mbsf) corresponds to the basement rocks of the sedimentary sequence, and is clearly identified by a sharp shift in the baseline of natural gamma ray, density, and resistivity logs. Compared to the sediments above, the basement unit shows a markedly higher average density and resistivity (2.3 g/cm^3 and 2.5 ohm.m) and lower porosity (about 20%).

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 clearly display vertical bands of large borehole radius in the interval 292-885 mbsf, interpreted as borehole breakouts caused by differences in the principal horizontal stresses. The average azimuth of the breakouts is roughly N-S to NNW-SSE, indicating that the maximum horizontal stress is oriented E-W to ENE-WSW.

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