IODP Expeditions 367 and 368: South China Sea Rifted Margin

Site U1499 Summary

Background and Objectives

Site U1499 is located on basement "Ridge A" within the South China Sea continent-ocean transition (COT) about 60 km seaward and SE of a basement structure labeled the Outer Margin High. The goal of drilling here was to core through the sediments to sample the basement rocks, to determine basement age and lithology. This would provide a test of different possible models for the processes and rheology controlling the extension and ultimate breakup of the continent. Ridge A was expected to have basement of either upper continental crust, lower continental crust, or mantle rocks, which might or might not have been serpentinized. The coring and drilling will also constrain the postrift history by determining the age, water depth, and subsidence rates of the overlying sedimentary packages.

Operations

We conducted operations in two holes at Site U1499 (proposed site SCSII-14A). Hole U1499A is located at 18°24.5698′N, 115°51.5881′E in a water depth of 3760.2 m. In Hole U1499A, advanced piston corer (APC)/extended core barrel (XCB) coring penetrated from the seafloor to 659.2 m and recovered 417.05 m (63%). Hole U1499B is located at 18°24.5705′N, 115°51.5990′E in a water depth of 3758.1 m. We installed casing in Hole U1499B to 651 m followed by rotary core barrel (RCB) coring that penetrated from 655.0 to 1081.8 m and recovered 150.64 m (35%). Coring terminated in gravels before deteriorating drilling conditions prevented further penetration—no crystalline basement was encountered. Despite challenging conditions in the lowermost part of Hole U1499B, two successful wireline logging runs were conducted from 652 to 1020 m.

Principal Results

Lithostratigraphy

The cored sediment at Site U1499 is divided into nine lithostratigraphic units. Lithostratigraphic Unit I is a 48.85 m thick middle–upper Pleistocene sequence of dark greenish gray bioclast-rich clay with thin clayey silt and sand interbeds. Fining-upward silty and fine sand intervals are abundant and interpreted as turbidite sequences. Four thin (2–7 cm) ash layers were identified in Unit I; none are observed in units below. Unit II (48.85–100.04 m) is a 51.19 m thick lower-middle Pleistocene sequence of interbedded greenish gray clay-rich calcareous ooze and dark greenish gray nannofossil-rich clay. Synsedimentary deformational structures such as folds, microfaults, and inclined beds are well developed in sediment of this unit, which is interpreted as a slump deposit. This unit is underlain by Unit III (Pliocene−middle Pleistocene age), which is divided into Subunits IIIA (100.04–181.80 m) and IIIB (181.80–333.65 m). The 233.61 m of Unit III is dominated by dark greenish gray clay with very thin to thin clayey silt and calcareous sand intervals. Subunit IIIA contains clayey silt layers that are very thin (<1 cm), whereas Subunit IIIB has abundant thin (2–5 cm) clayey silt layers and an overall increase in nannofossil and foraminifer content. Unit IV (333.65–404.90 m) is a 71.25 m thick sequence of upper Miocene-Pliocene dark greenish gray silty sand with clay interbeds. Recovery is very low throughout the section, but the recovered intervals suggest that the unit may contain unconsolidated to weakly consolidated sand.

Unit V (404.90–469.45 m) is a 64.55 m thick sequence of upper Miocene dark greenish gray clay with mostly thin (<5 cm) clayey silt and foraminifer sand interbeds. Drilling disturbance, in the form of biscuiting, increases significantly in this unit. Similar to Unit IV, recovery in Unit VI (469.45–618.30 m) is also very low. The recovered intervals in this unit include upper Miocene dark greenish gray silty sand with clay interbeds. Unit VII (618.30–761.70 m) is mainly composed of upper Miocene dark greenish gray to dark gray sandstone and claystone with siltstone interbeds. Lithification increases sharply downhole from the top of this unit, although sections with very low recovery are inferred to be nonlithified sand. Unit VIII (761.70–929.02 m) comprises a 167.32 m thick interval of Miocene reddish brown to reddish gray claystone and clay-rich chalk. Based on the abundance of calcareous material, this unit is divided into two subunits. Subunit VIIIA (761.70–892.10 m) contains lower-upper Miocene dark reddish brown claystone with siltstone and foraminifer sandstone interbeds, whereas Subunit VIIIB (892.10–929.02 m) comprises lower-middle Miocene reddish brown to reddish gray clay-rich nannofossil chalk and clay-rich chalk. In the lowest part of Subunit VIIIB, abundant brownish black iron-manganese nodules occur within reddish brown nannofossil-rich claystone.

Unit IX (929.02–1081.80 m) is readily distinguished from the overlying units by containing pre-Miocene sandstone, claystone, matrix-supported breccia, and gravel. This unit is 152.78 m thick and comprises three subunits. Subunit IXA (929.02–933.28 m) is defined by brownish and greenish gray sandstone and breccia. Subunit IXB (933.28–933.35 m) is defined by dark gray matrix-supported breccia in Core U1499B-30R. Subunit IXC (933.35–1081.80 m) contains gray to dark gray gravel with silty sand intervals. The cores in Subunit IXC are completely fragmented and recovered as pebbles and cobbles. In general, the pebbles and cobbles are recycled sedimentary rocks (such as sandstones), which contain a variety of individual lithic components including igneous, sedimentary, and metamorphic grains. However, the matrix that likely surrounded these cobbles and pebbles was not recovered; we inferred the matrix is poorly consolidated and washed away by the drilling process.

Structural Geology

The tilting of sedimentary beds and deformation structures observed at Site U1499 are limited to lithostratigraphic Units II, VII, VIII, and IX. The folds, faults, and tilted beds observed in Unit II are related to two slump events, which reworked older sediments between younger Units I and III. Tilted beds and faults with slickensides are observed in Unit VII and VIII. These faults are linked to compaction processes of the clays and the tilted beds are associated with sandy layers. Unit IX is divided into three subunits. In Subunit IXA, tilted beds as well as a downhole increase in clast size, angularity, and proportion of clasts is observed. The matrix-supported breccia of Subunit IXB exhibits no clear deformation structure or tilted sedimentary bedding. Some of the sandstone and breccia clasts in Subunit IXC exhibit veins and fractures. These clasts were transported before sedimentation; therefore, their veins and fractures must have originated in some previous tectonic event.

Biostratigraphy

All core catcher samples at Site U1499 were analyzed for calcareous nannofossil and foraminiferal content and additional samples were taken from the split-core sections when necessary to refine the ages. Preservation of microfossils varies from poor to very good and total abundance from barren to abundant. Although samples exhibit some degree of reworking, 28 biostratigraphic datums are recognized, revealing that we recovered an apparently continuous succession of Oligocene to Pleistocene age, spanning nannofossil zones NN5–NN21 and foraminiferal zones M4/M3 to PT1b. The Pleistocene/Pliocene boundary is located between Cores 367-U1499A-20X and 27X, and the Pliocene/Miocene boundary is located between Cores 367-U1499A-31X and 43X. Sedimentation rates varied from ~8 cm/ky in the Late Miocene to the Early Pliocene, ~5 cm/ky in the Early Pliocene to the Early Pleistocene, to ~13 cm/ky in the Middle–Late Pleistocene. Extremely low sedimentation rates (~1 cm/ky) occurred in the Early to Late Miocene during deposition of Unit VIII. The succession of Unit IXA comprises Late to Early Oligocene microfossils with calcareous nannofossils that are well preserved and abundant, while foraminifers are sorted or sparse. This indicates that Unit IX is probably transported and reworked.

Paleomagnetism

Paleomagnetic analysis was conducted on both archive-half sections and discrete samples from the working half. The archive-half sections were measured with the pass-through superconducting rock magnetometer (SRM) with demagnetization steps at 5, 15, and 25 mT. The discrete samples were subjected to alternate field (AF) and thermal demagnetization, and the remanence was measured on the spinner magnetometer. We adopted a combination of stepwise AF and thermal demagnetization steps to fully demagnetize the discrete samples and obtain the characteristic remanent magnetization (ChRM).

Variations in the natural remanent magnetization (NRM) intensity are well correlated to observable changes in lithology and the magnetic susceptibility. For example, the low NRM intensity at ~60 m (Core U1499A-7H) agrees with the carbonate-rich slump in which the magnetic susceptibility values are also low. The drilling induced remanence could be identified and removed in most core sections at AF treatments of 15 mT. In addition, magnetic mineral variations could be observed from the demagnetization behavior. From Core U1499B-12R on, the drilling overprint becomes stronger and hard to remove with the relatively low AF steps used on the archive-half sections, while AF treatments up to 200 mT and temperatures up to 675°C cannot fully demagnetize the discrete samples; these characteristics confirm the presence of hematite and magnetite.

We constructed a Site U1499 magnetostratigraphy based on the interpretation of the raw paleomagnetic data with stable and clear demagnetization behaviors. Core orientation from 0 to 162 m was used to correct the declinations; below that, our interpretation is only based on inclination data. When comparing to the standard geomagnetic timescale, we obtained several tie points., For example the Brunhes/Matuyama Chron boundary (0.78 Ma) is at ~110 m, and the middle of C2An.3n subchron is placed at ~260 m. We thus conclude that the Middle/Early Pleistocene boundary (0.78 Ma) is at ~110 m, the Early Pleistocene/Late Pliocene boundary is at ~220 m, the Late/Early Pliocene (3.6 Ma) boundary is at ~260 m, and Early Pliocene/Late Miocene boundary (5.33 Ma) is at ~370 m.

Geochemistry

Geochemical analyses were conducted for (a) headspace gas safety monitoring, (b) quantification of sediment $CaCO_3$, organic carbon, and nitrogen content, and (c) interstitial pore water characterization. Calcium carbonate contents vary between 0.4 and 82 wt%, with higher values of >20 wt% corresponding to intervals of nannofossil/foraminifera ooze or chalk. Total organic carbon (TOC) contents mostly range from ~0 to ~1.0 wt%. The TOC decreases gradually downhole from 1.0 to 0.3 wt% in the uppermost 110 m corresponding to the base of sulfate reduction zone, reflecting active degradation of sedimentary organic matter. The TOC to total nitrogen molar ratio (C/N) is mostly <8, indicating that TOC is derived dominantly from a marine source.

Hydrocarbon monitoring shows headspace gas consistently approaching zero throughout the site. Relatively higher methane contents of ~tens to 6000 ppmv occur across ~100–250 mbsf, just below the sulfate reduction zone. The overall low methane content indicates limited microbial methanogenesis likely due to low TOC contents <0.3 wt% below 110 mbsf.

We obtained 58 interstitial water samples from Hole U1499A. The inorganic geochemistry of interstitial waters is controlled by the remineralization of organic matter as well as carbonate and clay diagenesis. The sediment rapidly become suboxic, as indicated by a Mn peak of ~120 µM at ~6 m. Sulfate reduction coupled with sedimentary organic matter degradation occurs until ~110 m, with near-complete depletion until 257 m, before increasing slowly to 16.9 mM at the bottom of Hole U1499A. The interval of near-complete sulfate consumption is also marked by pronounced high Ba concentrations >50 µM, suggesting the dissolution of barite ($BaSO_4$). The peak alkalinity and steady increase in NH_4^+ and Br^- in the upper 110 m are consistent with progressive remineralization of sedimentary organic matter. The gradual decrease in Ca^{2+} above 80 m suggests active authigenic carbonate precipitation triggered by sulfate reduction. A subsequent downhole increase in Ca^{2+} and Sr^{2+} is likely caused by biogenic carbonate dissolution and recrystallization. Nearly parallel downhole decreases in Mg^{2+} and K^+ are mostly driven by clay mineral cation exchange and/or clay mineral authigenesis. The lower Cl^- and Na^+ concentrates compared to seawater at the bottom of the Hole U1499A are mostly driven by the smectite-illite transformation. Elevated Si concentrations of 700–820 µM from the seafloor to 45 m suggest active dissolution of biogenic silica.

Petrophysics

At Site U1499 measurements of *P*-wave velocity, bulk density, magnetic susceptibility (MS), and natural gamma radiation (NGR) were made on whole-round cores, and additional measurements were made on split cores and discrete samples, including thermal conductivity, caliper *P*-wave velocity (PWC), porosity, and bulk, dry, and grain density. In general, bulk density, *P*-wave velocity, and thermal conductivity increase with depth, whereas porosity decreases with depth as a result of compaction and lithification. However, some properties, such as NGR or MS, show local variations related to the specific lithology. The soft sediment in the upper 100 m shows rapid compaction with depth, marked by a decrease in porosity and increase in bulk density and thermal conductivity. Four thin volcanic ash layers in the top 50 m are marked by peaks in MS. The mass transport deposit (48.85–100.04 m) displays low MS and low NGR counts, reflecting the high carbonate content of the calcareous ooze. Below these layers down to ~890 m, physical properties show small variations; bulk density, *P*-wave velocity, and thermal conductivity gradually increase while porosity decreases with depth. The NGR and MS data in this interval do not show much variation. From 830 to 930 m, we observe a general decrease in MS values and NGR counts where the density increases slightly and the *P*-wave velocity increases significantly from 2200 to 2900 m/s. These variations are associated with a significant increase in the carbonate content in the Unit VIIIB chalks. The cobbles and pebbles in the deepest part (930–1080 m) show large variations in NGR, bulk density, and *P*-wave velocity, and very low MS.

Downhole Measurements

Two downhole logging tool strings were run in Hole U1499B, a modified triple-combo (sonic velocity, NGR, bulk density, resistivity, caliper) and the Formation MicroScanner (FMS resistivity images and calipers, NGR). Borehole conditions from the bottom of the casing at ~651 m to the bottom of Hole U1499B at ~1020 m were generally good, with measured diameters from ~10 to 16 inch. Washout zones are observed from 670 to 710 m, which corresponds to an interval of very low core recovery, as well as from 830 to 920 m, affecting quality of the log data in these intervals. Log and core data generally show good agreement. Downhole logging provided information in zones of poor core recovery in Hole U1499B. The log data from 726 to 739 m exhibits high NGR values and low bulk density and *P*-wave velocity, whereas the data from 820 to 840 m is characterized by a sharp increase in bulk density, a slight increase in *P*-wave velocity, and an abrupt decrease in NGR values compared to average values above and below these depths. The Unit VIIIB chalks (~890–930 m) display a sharp decrease in NGR and an increase in bulk density and *P*-wave velocity with depth, as well as only small variations in resistivity. Below 930 m, bulk density, *P*-wave velocity, and resistivity show large variability, in part due to the presence of cobbles and pebbles. The quality of acquired FMS images are strongly influenced by the hole diameter variations. They generally show alternating smooth and patchy textures with contrasting resistivity values marking horizontal to slightly tilted bedding down to 930 m. The deepest layers of sandstones, breccias, and gravels show highly variable and oblique textures on the FMS images, possibly reflecting the varied orientation of the gravel clasts, or the presence of faults and fractures in the gravel or the matrix. In general, the velocities measured with the sonic velocity logging tool match the PWC measurements taken with the caliper on the split cores. Six in situ formation temperature measurements were made in Hole U1499A which give a geothermal gradient of 93°C/km. The estimated heat flow is 110 mW/m^2, a value in agreement with the general heat flow of the area.

Correlation to Seismic Data

We used downhole log data, physical properties measurements on cores and samples, as well as other available data to correlate Site U1499 data with the available seismic reflection profiles. We also used the Site U1499 density and sonic velocity data to create synthetic seismograms that provided additional constraints on the correlation. Log sonic velocities and PWC velocities are in very good agreement, except for the deepest breccias and gravels (below ~930 m) where measurement on individual pebbles leads to an overestimate of the velocity in the formation. For seismic correlation, we use the PWC values and density values from moisture and density and gamma ray attenuation measurements from Hole U1499A (0–655 m), while below we used the downhole logging velocity and density data. We used a constant velocity of 2100 m/s in the low-recovery zones (333–406 m and 531–561 m), interpreted to be sandy layers, based on the downhole logging velocity values measured at greater depth. The comparison of the time-depth relation (TDR) obtained for Site U1499 to those for ODP Site 1148 as well as IODP Sites U1431 and U1433 shows substantial agreement, except for the Site 1148 TDR, which shows higher velocities in the deeper layers. The comparison between the seismic reflectors and the variations in physical properties and lithology characteristics using the computed Site U1499 TDR shows a good correlation between the main upper reflectors and the poor recovery sandy intervals. On the contrary, the main physical properties changes related to the top of the deep gravel layer do not correlate to the reflector observed at ~5.9 s in the seismic profile.