IODP Expeditions 367 and 368: South China Sea Rifted Margin

Site U1501 Summary

Background and Objectives

Site U1501 (Proposed Site SCSII-41A; 18°53.0923′N, 115°45.9455′E) within the South China Sea (SCS) northern margin is located on a broad regional basement high named the Outer Margin High (OMH). The OMH is the most landward of four distinct highs within the Continent-Ocean-Transition (COT), and is followed seawards by Ridges A, B, and C. Site U1501 is located near the crossing of seismic lines 15eclLW8 and 15eclLW1 in 2846 m water depth. Small rift basins are located on top of the OMH. These basins can be traced landwards into much deeper half-graben basins that formed during the main phase of crustal extension. The rift basins located on the OMH therefore offer options to recover the stratigraphy of these basins by moderately deep drilling, test existing stratigraphic interpretations, and extrapolate the findings margin wide. The recovery and characterization of these sequences are key objectives of Site U1501; the specific goals are to constrain the timing and duration of crustal extension, the tectonic vertical movements during rifting, and the subsequent, postrift thermal subsidence. The crystalline basement at Site U1501 is, in all likelihood, located far below the Tg seismic reflector horizon and is not an objective for this site.

The dip of the post-Tg strata within the fault block drilled at Site U1501 is estimated on seismic profiles to be ~5° towards the northeast, and likely to be close to the actual dip. The normal faults associated with the block rotation are estimated to dip in the range of 55° to 65° towards the southwest.

The faults offset the Tg reflector by as much as 75 ms (TWTT; 90–120 m pending seismic velocities), but much less offset, if any, is interpreted at the T60 unconformity. The main faulting is therefore interpreted to be younger than Tg and mostly older than the formation of T60 unconformity. This stratigraphic interval is therefore an important objective with regards to the timing and environment of rifting, including vertical crustal movements. The nature of the profound, basin-wide T60 unconformity is also an objective. The sedimentation rate of the post T60 interval is anticipated to constrain the rate of thermal subsidence following initial tectonic subsidence.

The water depth of 2846 m at Site U1501 makes it one of the few ODP and IODP sites within the SCS above the modern calcite compensation depth (CCD) of the SCS. The younger stratigraphy is therefore also the focus of some secondary scientific objectives related to Neogene environmental development of the SCS and adjacent landmasses of Southeast Asia. Amongst these are (1) to reconstruct the history of the East Asian monsoon evolution and that of deep water exchanges between the SCS and Pacific, and (2) to explore the sedimentary responses to the Cenozoic regional tectonic and environmental development of the Southeast Asia margin.

Principal Results

Lithostratigraphy

The sedimentary succession recovered at Site U1501 comprises clay-rich nannofossil ooze, silty clay, clayey silt, sand, and siltstone and sandstone with minor conglomerate and rare ash. The succession is divided into three major lithostratigraphic units—Lithostratigraphic Units I, II, and III—distinguished on the basis of sediment composition, particularly the relative abundance of the calcareous and siliciclastic fractions.

Unit I is a 303 m thick, Holocene–Late Oligocene succession, dominated by clay-rich nannofossil ooze and nannofossil ooze with clay, with minor amounts of nannofossil-rich foraminifer sand or silty sand. There is a felsic volcanic ash layer in Section 368-U1501A-1H-7A and an ash pod in Section 368-U1501C-3H-1A. Unit I is subdivided into six subunits: Subunit IA (0–25.47 mbsf), Subunit IB (25.47–66.17 mbsf), Subunit IC (66.30–156.70 mbsf), Subunit ID (156.80–191.99 mbsf), Subunit IE (191.99–293.09 mbsf), and Subunit IF (293.90–303.01 mbsf), based on changes in lithology, particularly the clay to nannofossil ratio and the presence and abundance of foraminifers and/or physical properties. The lower contact of Unit I is erosional and marked by the emplacement of a poorly sorted sandy layer. At the boundary, there are marked changes in *P*-wave velocity, natural gamma radiation (NGR), magnetic susceptibility, porosity, moisture and density, color, and carbonate content, but no discernible gap in sediment age. Unit I was deposited in a deep-marine environment, and lithological changes between subunits likely reflect the amount of terrigenous input into a relatively open ocean setting. This input may be delivered as buoyant plumes from shallower shelf environments and rarely by weak (distal) turbidity currents. Soft sediment deformation in Subunit IB indicates slumping downslope of parts of the sequence.

Unit II is 296 m thick and Late Oligocene to Late Eocene(?) in age. The unit consists of variable amounts of clay, silt, and sand with minor nannofossil-rich clay, nannofossil ooze, and silt with organic matter. There are gravel-size grains including shell fragments and glauconite, as well as carbonate and pyrite concretions. Unit II is subdivided into six subunits: Subunit IIA (303.01–385.26 mbsf), Subunit IIB (388.80–448.24 mbsf), Subunit IIC (452.60–482.33 mbsf), Subunit IID (491.00–519.80 mbsf), Subunit IIE (529.80–548.64 mbsf), and Subunit IIF (548.64–598.91 mbsf). The top two subunits define a fining-upward succession, from glauconite-sand dominated to siltstone and clay overlain by clay with nannofossils. Subunits IIC and IIE are dominated by sandstone with calcite, and Subunit IID has more fine-grained, organic-rich lithologies, while Subunit IIF is similar to Subunit IIB but has more coarse-grained sediment and distinctive weak red and reddish gray intervals between the green glauconite-bearing sands. Coarse sand- to pebble-size shell fragments are common in Unit II, and there are coral fragments in the upper part of the unit. Glauconite and quartz minerals dominate the siliciclastic grain component. Diagenetic pyrite is common. Unit II most likely represents a gradual change upwards from shallow (outer shelf or upper continental slope) to deep-water (lower slope) depositional environments. The Unit II/Unit III boundary was not recovered but is marked by an abrupt change in magnetic susceptibility, NGR, and *P*-wave velocity, so it is assumed that this boundary is sharp. A change in the apparent dip of strata from near horizontal in Unit II to approximately 20° in Unit III suggests that the contact is unconformable.

Unit III (598.91–644.3 mbsf [end of Hole U1501D]) is well lithified and comprises poorly-sorted, feldspar-rich sandstone interbedded with moderately to well-sorted, medium- to fine-grained sandstone, and rarely siltstone and poorly-sorted conglomerate. Unit III is divided into two subunits: Subunit IIIA (598.91–629.79 mbsf) and Subunit IIIB (629.79–643.56 mbsf). Subunit IIIA is composed of coarse-grained heterolithic sandstone, sandstone with calcite clasts, and minor conglomerate and siltstone. Pebble to cobble-size clasts include felsic intrusive and volcanic rocks, sedimentary rocks, metamorphic rocks, and rare gabbro. Subunit IIIB consists of sandstone and minor sandstone with organic matter. The subunit is finer grained than Subunit IIIA and has finely-laminated intervals. We speculate that Unit III was formed in continental to littoral environments with a provenance not far from the site.

Structural Geology

Lithostratigraphic Unit I has predominantly horizontal to subhorizontal bedding with local soft-sediment deformation structures such as slump folds. Unit I is devoid of any structures related to tectonic deformation, apart from some rare normal faults with minor offsets.

Lithostratigraphic Unit II is characterized by subhorizontal to gently dipping bedding. Steep dips of up to 40° are observed locally in close relation to parallel lamination and therefore interpreted as cross laminae. In contrast to Unit I, deformation structures are observed within Unit II, although their occurrence is heterogeneously distributed. Planar to irregular mm-scale normal faults and joints are observed in Subunit IIA typically with offsets ranging from 0.1 to 0.5 mm and apparent dips of 10° to 40°. Striations and slickensides occur where the surfaces of such structures are exposed. Deformation in the underlying Subunits IIC, IID, IIE, and IIF is characterized by randomly distributed, single to branched calcite and quartz veins. Recognition of deformational structures is difficult due to drilling disturbance throughout this unit.

The prominent Tg reflector marks the top of Lithostratigraphic Unit III. This unit shows a weak tilting of stratified beds expressed in apparent dips of up to approximately 20° on split core surfaces. Again, deformation structures remain scarce and heterogeneously distributed in Unit III. The recognized structures consist of veins, fractures, and local microfaults associated with cataclastic fault gouge.

In conclusion, despite the various tilting of reflectors (~5°) and the close proximity of extensional structures observed on seismic profiles, especially between T60 and Tg, only minor bedding tilting and/or deformation structures have been observed at this site. This may be due to the nature of the sediments and drilling disturbance.

Biostratigraphy

All core catcher samples at Site U1501 were analyzed for calcareous nannofossils, diatoms, and foraminifers, with select core catchers examined for ostracoda. Additional samples were taken from the split working-half sections when necessary to refine the ages between core catcher samples. Preservation of calcareous microfossils varies from good in Lithostratigraphic Unit I (Cores U1501A-1H, U1501B-1H, and U1501C-1H to 44X) to poor in Units II and III (Cores U1501C-45X to 62X, and U1501D-2R to 5R). Planktonic foraminifers and calcareous nannofossils are abundant in Unit I, common to rare in Unit II and upper Unit III, and barren in the rest of Unit III (Cores U1501D-6R to 27R). Diatoms are rare with moderate preservation in samples U1501A-1H-CC, U1501B-1H-CC, and U1501C-1H-CC and 2H-CC. The rest of the core catcher samples are barren of diatoms with the exception of Cores U1501C-3H-CC, 4H-CC, 33F-CC to 35F-CC, and 46X-CC in which diatoms are rare with poor preservation. Diatoms are common in burrows found in U1501C-35F-1W, 118–119 cm, with poor preservation.

Twenty-eight biostratigraphic datums were identified in a mostly continuous succession from the Middle Eocene to Holocene, with indications that Holes U1501C and U1501D penetrated into strata older than the Middle Eocene. The Pleistocene/Pliocene boundary (~2.6 Ma) is placed within Core U1501C-7H, the Pliocene/Miocene boundary (~5.3 Ma) within Core U1501C-9H, the Miocene/Oligocene boundary (~23.0 Ma) between Cores U1501C-41X and 42X, and the Oligocene/Eocene boundary (~33.9 Ma) below Core U1501C-45X. Sedimentation rates varied from ~11 mm/ky in the Miocene to ~14 mm/ky in the Pliocene and 24 mm/ky in the Pleistocene, respectively. Low sediment accumulation rates (~3.6 cm/ky) during the late Eocene through the early Oligocene and in the late Miocene suggest the presence of hiatuses in the sedimentary record during these periods. In contrast, higher sediment accumulation rates (35 mm/ky) existed during the Late Oligocene and the Early Miocene.

Predominance of shallow water benthic foraminifera and ostracoda assemblages in Cores U1501C-45X to 62X and U1501D-2R to 6R indicate an upper bathyal to continental shelf paleoenvironment during the Eocene to the early Oligocene. Predominantly abyssal benthic foraminifera and ostracoda above Cores U1501C-44X indicate that deep-water conditions existed in this part of the South China Sea since the early Oligocene.

Paleomagnetism

Paleomagnetic investigations combined measurement and in-line alternating field (AF) demagnetization of archive-half sections on the 2G Enterprises superconducting rock magnetometer (SRM) with the measurement of discrete samples demagnetized thermally or AF.

The rock magnetic experiments on six representative samples from Hole U1501C show SIRM/χ ratios between 12.8 and 14.6 kA/m, which indicates the predominance of greigite in Lithostratigraphic Unit I of Hole U1501C. The presence of greigite was documented with SEM in grains of 2–10 μm. Thermal demagnetization behavior also shows that greigite dominates the natural remanent magnetization (NRM), at least down to a depth of 83 m CSF-A. However, the magnetic remanence that remains above 575°C further suggests contributions from additional phases such as maghemite (TC ≈ 590-675°C) or hematite (TC ≈ 675°C).

Both AF and thermal treatments on discrete samples successfully removed the steep, low temperature/coercivity component, which represents the drilling overprint. The mean inclination gathered from the high-temperature component is 37.3° ± 6.6°, corresponding to a paleolatitude of 20.8° ± 3.3° for Lithostratigraphic Unit I. Many of the AF demagnetized discrete samples reveal trends showing reverse or normal polarity in the last step of demagnetization (50 mT) and are more difficult to interpret.

The magnetostratigraphy from Hole U1501C and U1501D is based on directions derived from the raw moments measured by the SRM at 25 mT and from the corroborative evidence from discrete samples. The magnetostratigraphy was correlated to the standard timescale and plotted along with the tie points from the microfossil ages from shipboard paleontologists. The paleomagnetic and paleontological age constraints match well over most of the section. A succession of eight normal and five reverse events was recognized in Hole U1501D. However, the lack of biostratigraphic constraints within all of Hole U1501D prevented even a tentative correlation of these events with the standard timescale.

Geochemistry

Interstitial water samples were obtained from depths down to 450 mbsf (Lithostratigraphic Unit IIB). Within Lithostratigraphic Unit I, variations are mainly the result of diagenetic and microbial processes, and measurements of alkalinity, phosphate, ammonia, and sulfate are within the ranges typical for the region (3.5–5 mM alkalinity, 250–510 µM phosphate, <30 µM ammonia, <26 µM sulfate). However, more atypically (particularly when compared with Expedition 367 Site U1499), the main changes associated with microbial processes are notable only within the first 25 m in Lithostratigraphic Unit IA, and are typical of organic matter degradation. Beneath this depth, within Unit I, changes in interstitial water chemistry appear inhibited until 300 mbsf. This may be a consequence of the low organic carbon concentrations and high carbonate content (~50%) of Unit I. Decreases in sulfate concentrations with depth are more pronounced in Lithostratigraphic Unit II (>300 mbsf) and within this zone there is heavy pyritization and total sulfur contents are high, suggesting sulfate reduction has taken place. Within the topmost part of Unit II (300 to 370 mbsf), chloride, bromide, and sodium are notably lower (chloride 500 cf 565 mM, bromide 0.75 cf 0.9 mM, and sodium 410 cf 480 mM). This difference in interstitial water chemical composition is sharp, and could result from pressure-isolated units retaining a distinct formation water-chemistry or from the migration of chloride-poor formation water.

Headspace gas concentrations were beneath background-laboratory levels in all samples collected from Site U1501 (<1% ppmv). Total organic carbon content was typically less than 0.5 wt% in Unit I, except from 0 to 50 mbsf (Unit IA). Within this interval is a typical black marine mud with a TOC of about 1 wt%. Total organic carbon was also typically less than 0.5 wt% in Lithostratigraphic Units II and III, except for a few carbonaceous lithologies; sandstone with plant-phytoclasts associated with an ash-rich boghead coal in Unit II (U1501D-9R-1, 10–15 cm), and a bitumen-impregnated sandstone in Unit III (U1501D-27R-1, 12–16 cm). Total sulfur content is low in Unit I: ~1 wt% in Subunit IA, and beneath effective shipboard detection limits of 0.01 wt% for the rest of Unit I. Total sulfur content is higher in Unit II: the muddier-topmost part of Unit II has values greater than 1 wt%, whereas the sandier deeper part averages about 0.5 wt%.

Elemental compositions primarily reflect geological units and changes in lithology. Within Unit I, carbonate contents are high, and within foraminifer-rich intervals they exceed 50 wt% (compositionally a limestone). Within Units II and III, carbonate is less common and the units are predominantly siliciclastic, with a distinction between units that are mud-rich and feldspathic, and sandier units toward the base of the hole. Calcium along with strontium is associated with biogenic sediments in Unit I, but in deeper units covaries with aluminium. Within the base of Unit II and in Unit III, sodium and potassium are both high, consistent with the presence of feldspathic sediments. The higher aluminum proportion within the top of Lithostratigraphic Unit II is consistent with the muddier, clay-rich lithologies present here.

Physical Properties

Four physical properties units were defined at Site U1501. Unit 1 (0–300 mbsf) experienced the most evident changes in sediment compaction, which is expressed by increasing bulk density (1.4 to 2.0 g/cm^3), *P*-wave velocities (1450 to 1930 m/s), and decreasing porosity (85% to 45%) with increasing depth. As Unit 1 consists mostly of calcareous ooze, it shows relatively low natural gamma radiation (NGR; between 20–40 cps) and magnetic susceptibility (MS) values (between 10–60 × 10^{-5} IS). The onset of Unit 2 (300–450 mbsf) is marked by a rapid increase in NGR and porosity values but a rapid decrease in bulk density and *P*-wave velocity, corresponding to a shift to a different lithological unit with sand, silt, and clay-enriched sediments. Within the whole unit, NGR has persistently high readings between 60–80 cps, while MS values remain as low as 10 × 10^{-5} IS. *P*-wave velocity and bulk density continue to show an increasing trend with core depth. Most physical properties of Unit 3 (450–600 mbsf) have similar values to Unit 2, except that *P*-wave velocity shows extremely high values up to 4000–6000 m/s at some interbeds, and bulk density and porosity increase and decrease up to 2.6 g/cm^3 and 2%–3%, respectively. Unit 4 (600–657 mbsf) is distinct from other units due to higher mean values of NGR (80 cps), bulk density (2.6 g/cm^3), and MS (500 × 10^{-5} IS), as well as *P*-wave velocity (4500 m/s). Along the whole cored interval (0–657 mbsf), thermal conductivity shows an increasing trend from 0.7 to 3.4 W/(m·K), most likely due to increasing sediment compaction as well as changes in sediment compositions. The L*, a*, and b* show trend patterns mainly controlled by carbonate content and sandy layers.

Downhole Measurements

Wireline logging using a triple combo tool string was conducted in Hole U1501D. The modified triple combo tool string included the Hostile Environment Natural Gamma Ray Sonde (HNGS), Hostile Environment Litho-Density Sonde (HLDS), High-Resolution Laterolog Array (HRLA), and magnetic susceptibility sonde (MSS). The triple combo run collected good data in the interval of 115.1 mbsf (end of drill pipe) to 299 mbsf, where it encountered an obstruction. Four logging units were defined. Logging Unit 1 (base of drill pipe to 190 mbsf) is characterized by intervals of large hole diameter, and relatively high variability in NGR and MS. Logging Unit 2 (190–260 mbsf) is characterized by a relatively constant hole diameter, relatively homogeneous logs, and sub-meter-scale layering. Logging Unit 3 (260–275 mbsf) again shows relatively large hole diameter, as well high variability in NGR, density, and resistivity logs. Logging Unit 4 (275–300 mbsf) exhibits relatively large values of resistivity and MS. The upward log pass indicated a collapsed hole at ~156.3 mbsf on the caliper curve, and for safety reasons, no further attempts to descend below that under-gauge spot were made. Because the interval of the collapsed hole was located only ~40 m below the bottom of the pipe, the originally planned FMS-sonic tool string was not run. Four in situ formation temperature measurements were made in Hole U1501C, yielding a geothermal gradient of 81.4°C/km and a calculated heat flow of 100.1 mW/m^2. These values are comparable to the relatively high values observed in ODP and IODP sites in this part of the South China Sea.