IODP Expeditions 367 and 368: South China Sea Rifted Margin

Site U1502 Summary

Background and Objectives

Site U1502 (proposed Site SCSII-17A) within the South China Sea (SCS) northern margin is located in a water depth of 3764 m on a prominent basement ridge (Ridge A) within the Continent-Ocean-Transition (COT). Ridge A is one out of four distinct basement highs found across the COT. The Outer Margin High (OMH) is the most landward of these highs within the COT, and it is followed seaward by the nearly parallel Ridges A, B, and C. A key objective of Expeditions 367/368 is to examine the nature of the crust within Ridge A. This ridge is considered to be a pivotal element in the transition from continental to oceanic crust. Hence, the main objective of Site U1502 was to drill through synrift deposits overlying an interpreted, shallow-dipping (~20°) fault zone and into the crystalline basement below the fault. Information on the nature and age of the synrift deposits overlying the fault, as well as the nature and age of the overlying sediments and associated seismic unconformities, formed another target with the objective of constraining basin subsidence.

Operations

We conducted operations in two holes at Site U1502. Hole U1502A is located at 18°27.8720′N, 116°13.8381′E, in a water depth of 3763 m. Our operations in Hole U1502A were designed to provide information on formation characteristics and drilling conditions so that we could decide the length of casing to drill into the seafloor at the second, deep penetration Hole U1502B. Given this purpose and the amount of time needed to drill the second, deep hole, we did not core continuously in Hole U1502A. Instead, we (a) drilled without coring from the seafloor to 375.0 m, and (b) rotary core barrel (RCB) cored from 375.0 to 758.2 m and recovered 176.81 m (46%). Hole U1502B is located at 18°27.8798′N, 116°13.8409′E, in a water depth of 3763.6 m. In Hole U1502B, we (a) drilled a reentry funnel and 727.7 m of 10.75 inch casing into the seafloor, (b) RCB cored the sediment-basalt transition (727.7 to 739.16 m) and 180 m into the underlying basalt (739.16 to 920.95 m; 128 m recovered, 70%), and (c) collected downhole log data with the triple combo tool string and a check shot with the Versatile Seismic Imager (VSI) tool.

Principal Results

Lithostratigraphy

The sedimentary succession recovered at Site U1502 extends from the late Eocene to the late Miocene. The succession includes four sedimentary units (Unit I, and Units III to V) that comprise mainly clay, nannofossil-rich clay, biosiliceous-rich clay, limestone, and clast-rich clay, and two igneous units that are mainly composed of basalt (Unit II and VI). The base of the sedimentary succession is a sequence of clay and metasediments (dolomite marble and dolomitic limestone) possibly forming the contact with a unit of altered basalt (Unit VI).

Late Miocene to late Oligocene Lithostratigraphic Unit I is divided into five subunits. Subunit IA (Hole U1502A, 375.00–486.82 m) is composed of dark gray, gray, dark greenish gray, and greenish gray silty clay, clay with nannofossils and nannofossil-rich clay intercalated with dark grayish brown, grayish brown, and brown clay with nannofossils. There is minor dark greenish gray sandy clay with calcite. Subunit IB (Hole U1502A, 490.20–599.57 m) is composed of alternating intervals of brown and greenish gray clay, silty clay, and clayey silt. Sandy intervals are rare. The recovery in Subunit IA and IB was very poor, which might be due to the occurrence of thick sand beds that were washed out. Subunit IC (Hole U1502A, 599.57–602.39 m) is composed of greenish gray and reddish gray foraminifer-rich clayey siltstone to sandstone with parallel lamination and convolute bedding. There are also thin layers of pinkish gray foraminiferal chalk. Subunit ID (Hole U1502A, 602.39–724.03 m) is mainly composed of alternating greenish and brownish gray and grayish brown clay, silty clay, clayey silt, and clay with silt (Cores U1502A-25R to 32R), but brown colors dominate from Core U1502A-33R to 38R. Nannofossils are abundant within the lowermost ~4 m of this subunit. Subunit IE (Hole U1502A, 724.03–734.87 m; Hole U1502B, 727.79–727.96 m) is composed of brown nannofossil-rich clay with foraminifers and nannofossil-rich clay with pale green colors as haloes around fractures. The sediments of Unit I are interpreted as being deposited in a deep marine environment. Fining upward intervals in Subunits IA to IC are interpreted as turbidites.

Unit II is a highly-altered, greenish-gray, basalt clast recovered from Hole U1502B at 727.96–728.04 m. The primary mineral phases are replaced by an alteration mineral assemblage.

Unit III (Hole U1502A, 739.10–739.16 m; Hole U1502B, 728.04–733.82 m) is composed of a brownish yellow, silicified, very hard, poorly-sorted breccia. The granule to pebble size clasts consist of alteration minerals (Fe-hydroxides) cemented by a matrix of annealed quartz in various grain sizes.

Unit IV consists of a biosiliceous-rich silty clay. Diatoms, sponge spicules, and radiolaria are abundant in the upper part, but both the abundance of nannofossils and diatoms decreases rapidly downwards from Section U1502A-40R-1 to 40R-3. Pyrite occurs as centimeter-size patches and along cracks. The layering in Unit IV is inclined and may be slightly deformed.

Unit V (Hole U1502A, 747.20–749.01 m; Hole U1502B, 733.82–739.16 m) is an interval of alternating metasediments (dolomite marble, dolomitic limestone, clast-rich clay). The dolomite marble is dominated by very fine-grained dolomite (~95%) with minor amounts of magnetite (~3%) and calcite (~2%). The annealing texture is equigranular and crossed by fine-grained dark gray bands. The presence of magnetite explains the extraordinary high magnetic susceptibility of this unit. The gray, fine-grained dolomitic limestone in Hole U1502B is intercalated with well-consolidated, very dark greenish gray clay with 10%–15% igneous clasts. The sediment is overprinted with alteration caused by secondary high temperature processes (e.g., hydrothermal fluid sediment interaction or contact metamorphism).

Unit VI (Hole U1502A, 749.01–750.67 m; Hole U1502B, 739.16–920.95 m) consists of highly altered basaltic breccia, brecciated basalt, pillow basalt, and sheet basalt. The unit is divided into two subunits. Subunit VIA is composed of highly altered basaltic breccia and brecciated basalt with minor sheet basalt, chert and claystone, and very minor pillow basalt. Subunit VIB is dominated by pillow basalt and sheet flows and is less brecciated than Subunit VIA.

Structural Geology

Deformation structures are scarce in Lithostratigraphic Unit I until Core U1502A-37R, only showing locally a convolutely bedded sequence in Core U1502A-25R. Starting from Core U1502A-37R at ~700 m, a gradual increase in deformation structures is observed. Cores U1502A-37R, 38R, and 39R are characterized by microfaults, evidenced by down-dip plunging striations and slickensides on exposed fracture surfaces, systematically associated with greenish halos. No deformation structures were encountered in Unit II. Lithostratigraphic Unit III consists of an extremely silicified breccia that was poorly recovered. However, the nature of this breccia as sedimentary, tectonic, or hydrothermal remains unconstrained at the moment. In Lithostratigraphic Unit IV a small-scale transition from distributed to localized shear in unlithified sediments of Unit IV is documented. No deformation structures were encountered in Unit V. Lithostratigraphic Unit VI is essentially composed of basalts that were heterogeneously affected by brecciation and veining associated with the circulation of hydrothermal fluids. Subunit VIA is dominated by brecciated basalt/basaltic breccias, whereas Subunit VIB comprises a rather coherent series of lava flows, crosscut by a multistage network of polymineralic veins.

The very top of Unit VI contains severely fractured and fragmented basalt locally filled by fine-grained unconsolidated greenish rocks. The Subunit VIA is characterized by diverse brecciation horizons associated with veins and microcracks. Depending on the intensity of fragmentation, as well as the clast/matrix ratio, the rocks are referred to as brecciated basalt or basaltic breccia. A typically observed feature is the jigsaw-puzzle structure, suggesting a possible in situ fragmentation. Macro- and microscopic observations show that the breccia-clasts consist mainly of sparsely to moderately plagioclase phyric basalts that were hydrothermally altered to variable degrees. Thus, formation of such breccias likely involved fluid-assisted fracture of basalt. In contrast, Subunit VIB is characterized by progressive decrease of breccia horizons and the development of different vein types, almost always polymineralic. Notably, vein composition and orientation changes through Subunit VIB. Although numerous small-scale veins often related with major ones can be observed, at a first-order, three vein types were categorized: 1) composite silica-rich veins, 2) composite epidote-rich veins, and 3) composite carbonate and/or silica-rich veins.

Biostratigraphy

All core catcher samples from Hole U1502A and selected samples from Hole U1502B were analyzed for calcareous nannofossils, foraminifers, diatoms, and ostracods. Additional samples were taken from intervals within the working-half cores when necessary to refine the ages. The preservation of calcareous microfossils is mostly good to moderate in the upper sections (Cores U1502A-2R to 13R), to moderate to poor in the lower sections (Cores U1502A-14R to 41R). Planktonic foraminifers and calcareous nannofossils are abundant to common in Cores U1502A-2R to 10R, U1502A-25R, and U1502A-37R to 39R, and rare to barren in all other sections. Diatoms are only observed in Sections U1502A-40R-1W to 3W. In Hole U1502B, foraminifers were observed only in Sample U1502B-3R-1W, and are represented by well-preserved agglutinated, deep-water taxa. Ostracoda are extremely rare and single occurrences were observed only in three samples in Hole U1502A (U1502A-3R-CC to 5R-CC).

Fourteen planktonic foraminifer and calcareous nannofossil biostratigraphic events were used to provide an age-depth model for Site U1502 from the Late Miocene to Late Oligocene. The Pliocene/Miocene boundary is placed tentatively within Core U1502A-2R, but it may be above the cored section; and the Miocene/Oligocene boundary was determined to lie between Samples U1502A-39R-CC and U1502A-40R-1W, 7 cm. Sedimentation rates varied from ~39 mm/ky in the Late Miocene, to ~10 mm/ky in the Middle and Early Miocene. No planktonic microfossils were found in Hole U1502B, but a sample from a sandy interval in Core U1502B-3R revealed abundant and diverse abyssal agglutinated benthic foraminifera. The composition of this agglutinated benthic foraminifer assemblage provides a possible age of late Eocene for this interval.

Paleomagnetism

The magnetic behavior of sediments at Site U1502 correlates with their color (greenish gray or reddish brown). Reddish brown sediments show an AF magnetization indicative of magnetite or titanomagnetite and hematite (responsible for the color). In contrast, greenish gray sediments host magnetite or titanomagnetite and pyrrhotite. The predominance of steep normal inclinations (~75°) across all late Oligocene to late Miocene units (375.00–750.67 m) affects the SRM section measurements and prevents any reliable magnetostratigraphy to be established for both Holes U1502A and U1502B.

The basalt has natural remanent magnetization (NRM) intensities one order of magnitude higher than sediment. The main magnetically remanent phase is titanomagnetite, but its alteration produces maghemite or hematite. The magnetic susceptibility κ shows a bimodal distribution with a median at 327×10^{-6} SI. κ does not show any strong correlation with any chemical (R^2 = 0.343 for Fe^2O^3 wt%). Intervals of high κ values might correspond to bottoms of flows with a massive, less altered structure. Altered basalts have higher Koenisberger ratios (Q_n = 1–10) than fresher basalts (Q_n = 0.001–1). The mean dip of magnetic foliation is 8°, a relatively shallow value considering the dip of seismic reflectors corresponding to these basalts (14°). Cores

U1502B-9R and 10R show less pervasive drilling overprint, and two discrete samples show both a normal (soft) component and a reverse (hard) component, suggesting a possible reversal.

Geochemistry

Site U1502 contains very low high hydrocarbon gas abundances and total organic carbon, nitrogen, and sulphur contents. This likely reflects the poor preservation of organic matter. Instances of high carbonate content are associated with siderite, and on occasion this mineral comprises greater than 50% by mass of intervals of Lithologic Unit ID. The interstitial water at Site U1502 is enriched in Ca, Mg, and K, and has notably high alkalinity, but is depleted in Na, Cl, and Br. The linear decrease and increase of major anion and cation contents implies the upward movement of fluid from deep sediments. The hemipelagic sediments within Lithologic Unit I have some similarities to the geochemical characteristics of the hemipelagic and pelagic units at Site U1501, but Site U1502 sediments have distinctively higher iron, potassium, and clay concentrations likely due to regions of increased alteration. All of the analyzed igneous rocks from Units II to VI were altered, and in general samples from petrographic subunit 2b were altered to a lesser degree than those from subunit 2a.

Physical Properties

Petrophysical data acquired at Site U1502 include density, magnetic susceptibility (MS), *P*-wave velocity, natural gamma ray (NGR), color reflectance, and thermal conductivity. These data allow us to characterize four petrophysical units. PP Unit 1 (375–740 mbsf) corresponds to the nannofossil-rich and biosiliceous-rich clay lithologies, and exhibits small variations in natural gamma radiation between 50 and 70 cps, and uniformly increasing *P*-wave velocities with depth that are on average less than 2500 m/s. Sediments of PP Unit 1 show similar porosities to those recorded at nearby Sites U1499 and U1500 in the same depth interval, suggesting the same compaction history. A significant increase in bulk density (up to 2.7 g/cm^3) is observed in Core U1502B-3R and is associated with strongly lithified limestone beds. Variations of high and low MS values correspond to sediment color changes in PP Unit 1 and may be controlled by the amount of pyrrhotite within the sediments.

PP Unit 2 (740–750 mbsf) in Hole U1502A is characterized by lower *P*-wave velocities and bulk densities, and higher gamma ray readings than the strata above. Low densities and *P*-wave velocities suggest that PP Unit 2 is less compacted.

PP Units 3 and 4 represent the basaltic basement and are characterized by relatively low NGR values (less than 10 cps), high densities, and *P*-wave velocities that vary over a broad range (3000–6000 m/s). The limit between PP Units 3 and 4 is marked by an abrupt increase in densities, *P*-wave velocities, and thermal conductivity, and coincides with the change from Igneous Subunit 2a to 2b. Prominent magnetic susceptibility peaks (up to 4000 × 10^{-5} SI) in PP Units 3 and 4 correspond to relatively less altered basalt. Thermal conductivities in PP Units 3 and 4 are variable but with an overall trend to increasing values, in line with decreasing porosity with depth.

Downhole Measurements

Wireline logging was conducted in Hole U1502B using a modified triple combo and Versatile Seismic Imager (VSI) tool strings. The modified triple combo tool string included the Hostile Environment Natural Gamma Ray Sonde (HNGS), Hostile Environment Litho-Density Sonde (HLDS), and a Dipole Sonic Imager (DSI) for acoustic velocity. The triple combo run collected good data from 875.3 m (~45 m above the bottom of Hole U1502B), and it allowed us to define eight logging units, which correlate in great part to the Lithostratigraphic Units and core physical properties. Logging Units 1–5 are defined by data collected through the casing and drill pipe, and Unit 6 data was collected outside the casing but inside the drill pipe, while Unit 7 and 8 data were collected in the open hole. For measurements inside the casing and/or drill pipe, only natural gamma, and the associated potassium, thorium, and uranium components, provide meaningful data, though highly attenuated by the casing and/or the drill pipe. Open borehole conditions from the bottom of the casing at 723 m to 875.3 m were generally good, with measured diameters from 12 to 14.5 inch. Log and core data generally show good agreement, and downhole measurements provide information in zones of poor core recovery in Hole U1502B. The log data exhibit trends in increasing density and *P*-wave velocity with depth. The amplitude of NGR increases gradually with depth throughout units 1–3 (seafloor to ~630 m), with an interval of relatively constant values between 150 and 350 m. NGR values are lowest in units 4–8 (~630 to 850 m).

The VSI was run only inside casing because the tool could not pass through an obstruction encountered at the end of the casing. Eight stations were attempted. The two deepest ones (at 715.1 and 695.2 m) are associated with large noise levels possibly due to poor mechanical coupling of the casing with the surrounding formation. The remaining upper six stations, located at depths of 290.2, 350.3, 450.3, 550.1, 590.3, and 630.3 m, recorded good quality waveforms.