IODP Expeditions 367 and 368: South China Sea Rifted Margin

Site U1504 Summary

Background and Objectives

Site U1504 (alternate Site SCSII-27A) was proposed during Expedition 367 and approved by the Environmental Protection and Safety Panel during Expedition 368 as alternate sites should there be time left following completion of the high-priority sites included in the *Scientific Prospectus*. Expedition 368 decided to occupy Site U1504 following the inability to continue drilling below the 990 m deep cased Hole U1503A. A limitation on operations to a maximum depth of 3400 m (water depth plus penetration) was imposed by a failed drawworks low clutch diaphragm, and severely limited drilling options during Expedition 368 operations. Most of our remaining available sites were in water depths greater than 3400 m and/or required deep penetration. One exception was Site U1504 located in 2823 m of water depth with a shallow coring target.

Operations

Two holes were drilled at Site U1504. In Hole U1504A (18°50.9199′N, 116°14.5397′E, water depth 2816.6 m) we rotary core barrel (RCB) cored from the seafloor to 165.5 m and recovered 52.77 m (32%). In Hole U1504B (located ~200 m southeast of Hole U1504A at 18°50.8213′N, 116°14.5978′E, water depth 2843.0 m) we drilled without recovery to 88.2 m and then RCB cored to 200 m with 21.48 m of recovery (19%).

Principal Results

Lithostratigraphy

The succession recovered at Site U1504 includes two sedimentary units (Units I and II) which are underlain by a metamorphic unit (Unit III). Lithostratigraphic Unit I is dominated by nannofossil and foraminiferal ooze, and minor nannofossil-rich clay, and is divided into four subunits (Subunits IA to ID). Subunit IA (Hole U1504A, 17.50–46.59 m) comprises nannofossil-rich clay, nannofossil ooze, nannofossil ooze with biogenic silica, and clay-rich nannofossil ooze. The color of the ooze gradually changes downhole from dark greenish gray to greenish gray and gray. Distinct intervals contain more silt, and there are thin silt laminations that are often disrupted by bioturbation. Layering is contorted at the base of the subunit. Subunit IB (Hole U1504A, 46.59–59.73 m) comprises light brown foraminifer-rich nannofossil ooze and pale brown nannofossil ooze with foraminifers. Subunit IC (Hole U1504A, 65.80–104.99 m) comprises light greenish gray, greenish gray, light brownish gray, pale brown, and light gray nannofossil ooze with clay, and greenish gray clay-rich nannofossil ooze, intercalated with light gray nannofossil-rich foraminiferal ooze with clay, light brownish gray foraminifer-rich nannofossil ooze, and foraminifer-rich nannofossil ooze with clay. Subunit ID (Hole U1504A, 104.99–112.66 m; Hole U1504B, 88.20–92.31 m) comprises light brown to yellowish brown nannofossil ooze with foraminifers, intercalated with pink or brownish yellow foraminifer-rich nannofossil ooze.

Unit II (Hole U1504A, 114.72–134.80 m; Hole U1504B, 97.90–107.91 m) is clast-supported, bioclast-rich and clast-supported limestone with large benthic foraminifera (up to 15 mm). The contact between Unit I and II was not recovered.

Unit III (Hole U1504A, 136.40–163.70 m; Hole U1504B, 117.40–196.28 m) is composed of fine to coarse-grained epidote-chlorite schist (Subunit IIIA) and calc-silicate schist (Subunit IIIB), with granofels clasts.

Metamorphic Petrology

We recovered 27 m (Hole U1504A) and 79 m (Hole U1504B) of a variety of mylonitic epidote-chlorite to calc-silicate schists containing granofels clasts. Recovery was <20% in this unit. Lithological changes with depth and between the two holes was observed and the unit was subdivided based on a change in the predominant metamorphic lithology. Lithological Subunit IIIA was recovered in both Holes U1504A and U1504B, and consists of greenish gray, microcrystalline to coarse-grained epidote-chlorite schist with dark greenish gray granofels clasts (<10 cm) and epidote-chlorite breccia. The schists show a strong mylonitic foliation, while the clasts have generally isotropic textures showing, locally, a weakly developed foliation. In general, both the schist and the granofels clasts show a comparable mineral assemblage consisting of epidote, chlorite, feldspar, and quartz ± other phyllosilicates and accessory minerals and locally isolated subhedral dark minerals (pyroxene?). The granofels clasts are often crosscut by a network of quartz veins. Lithological Subunit IIIB comprises an alternation of calc-silicate schist and epidote-chlorite schist with granofels clasts, epidote and/or chlorite granofels, chlorite schist with epidote, epidote-chlorite gneiss, and minor marble. The lithologies are fine to coarse grained with mostly an inequigranular texture and some bimodal or equigranular textures, and the schistose sections show a strong mylonitic foliation. Several of the schists show a reddish-brown alteration, and late calcite veins crosscut the foliation of the deepest schists recovered (e.g. in Core U1504-20R). Minerals that can be observed are epidote, quartz, chlorite, calcite, and feldspar. Metamorphic subunit IIIB contains numerous clasts with variable lithologies: cryptocrystalline granofels, either with or without quartz and/or calcite veins, porphyritic rocks with tabular phenocrysts (possibly altered plagioclase), brecciated (epidote, calcite, and/or quartz) veins, and foliated granofels.

Handheld pXRF analyses show an average mafic igneous composition for both the schist and the clasts but with a spread towards ultramafic (in Subunit IIIA, Hole U1504B) and more felsic compositions (in Subunit IIIB). There is a clear change of several wt% in sulfur content between Subunit IIIA and Subunit IIIB, the latter of which is below the detection limit. High Nb contents compared to MORB indicate a potentially enriched source for the protolith.

Lithostratigraphic Unit III consists of mylonitic, greenschist facies metamorphic rocks as indicated by the presence of epidote and chlorite. We infer that the protolith most likely was a breccia, based on the different clast sizes and types, and styles of deformation. The protolith likely had a mafic igneous composition. However, it is unclear if this breccia with mafic clasts has a sedimentary origin (e.g. volcaniclastic) or represents a potentially hydrothermally altered form of basalt, gabbro, or ultramafic protolith. At present, the metamorphic evolution of this unit and its connection with the opening of the South China Sea is unknown.

Structural Geology

Lithostratigraphic Unit I shows subhorizontal bedding and locally some minor possible slump folds as observed in Section U1504A-5R-1. Lithostratigraphic Unit II is devoid of any deformation structures. The metamorphic basement at Site U1504 is formed by greeenschist facies mylonitic epidote-chlorite schists and calc-silicate schists (Lithostratigraphic Unit III). The rocks preserve distinct deformation structures resulting from changes in the mode of deformation (brittle/ductile), modal amount of quartz + feldspar governing the (local) rheological behavior, the amount of accumulated strain, the occurrence of variably sized (up to dm-scale), pre-kinematic, heterolithic clasts that mostly form rigid (i.e. internally undeformed) bodies within the ductile foliation, and/or superimposed multiple deformation phases. The steeply dipping (up to 75°) mylonitic foliation is characterized by distinct morphologies: (1) a widely spaced anastomosing foliation associated with leucocratic bands, (2) a tight, closely spaced, and often crenulated foliation associated with more melanocratic schist variations, and (3) a tight anastomosing foliation associated with calc-silicate schists enclosing angular to rounded heterolithic granofels clasts. Locally, the sense of shear is indicated by shear bands and sigma clasts. In Subunit IIIA, granofels clasts are consistently microcrystalline (chlorite + epidote) and dismembered by a network of mostly parallel and perpendicular quartz veins cutting each other. Often they form apparently stretched, elongated bodies oriented parallel to the foliation. Subunit IIIB shows a wide range of prekinematic (mostly mafic) clasts enclosed by the foliation. Encountered varieties encompass highly phyric to aphyric rocks, as well as fragmented former (epidote/calcite/quartz) vein fillings. In cases, such clasts show ductile internal deformation. Clast boundaries can be both distinctly sharp or diffuse, the latter indicating mechanical and/or chemical interactions with the surrounding foliation. Deformation in Subunit IIIB is presumably strongly controlled by an inherited (protolithic) brecciated structure.

Biostratigraphy

All core catcher samples at Site U1504 were analyzed for calcareous nannofossils, foraminifers, and diatoms. Additional samples were taken from intervals within the working-half cores when necessary to refine the ages. Preservation of calcareous microfossils is good to very good in Cores U1504A-2R to 12R and Core U1504B-2R, and poorly preserved below due to the recrystallization in the reefal limestone. Diatoms are poorly preserved in Cores U1504A-2R to 5R, while they are rare or barren in other core catcher samples. Planktonic foraminifera and calcareous nannofossils are abundant in Cores U1504A-2R to 12R and Core U1504B-2R, and barren in Cores U1504A-13R to 15R. Twenty biostratigraphic datums were identified in a succession from the Late Pleistocene to the Early Miocene.

A hiatus between the Early Pleistocene and Late Miocene was determined within Core U1504A-6R, with abrupt planktonic foraminiferal and nannofossil assemblage changes. Sedimentation rates at this site varied from ~22 mm/ky during the Pleistocene to ~6 mm/ky in the Early–Middle Miocene.

Cores U1504A-13R to 15R are mainly composed of reefal limestone with abundant larger benthic foraminifera occurring in Cores U1504A-14R and 15R. Thin section examination of these carbonate rocks indicated the presence of abundant *Nummulites,* suggesting an Eocene age. The abundant larger benthic foraminifera indicate deposition in a warm shallow marine environment. In contrast, the abundant planktonic foraminifera and calcareous nannofossils in the carbonate ooze in the overlying sedimentary section (Cores U1504A-2R to 12R) indicate a deep-water environment since the Early Miocene.

Paleomagnetism

Most of the 14 discrete sedimentary samples show an initial soft magnetic behavior attributed to titanomagnetite, followed by a gyroremanent magnetization above 70 mT attributed to greigite, a mineral already identified at Site U1501. Consistently steep normal inclinations (~60°) across all sedimentary units indicate a significant drilling overprint that is removed by alternating field (AF) demagnetization up to 15 mT. A succession of nine normal and eight reversal polarities can be defined, particularly in the upper part of the cores.

Discrete samples show low κ values, a moderate degree of magnetic anisotropy, and a strongly oblate symmetry, probably of depositional origin. This subhorizontal planar fabric attests of deposition in a calm, pelagic environment with moderate traction.

Natural remanent magnetization (NRM) intensities of metamorphic rocks, measured on the superconducting rock magnetometer (SRM) and on four discrete cubes, are relatively weak and attest of a complex magnetic assemblage comprising magnetite and hematite in one specimen. The anisotropy of magnetic susceptibility (AMS) fabrics consistently dip steeply, and show a moderate to high degree of magnetic anisotropy, oblate symmetries, and oblique magnetic lineations, possibly indicating an oblique motion within this high strain shear zone.

Geochemistry

Hydrocarbon gases were not detected above background levels at Site U1504, and total organic carbon, nitrogen, and sulfur contents were low (<0.5%). Instances of high carbonate content were associated with bioclast-rich and clast-supported limestone. The upper part of the sediment was not cored, hence present-day early diagenetic processes were not constrained. Pore water data are broadly comparable to other sites.

Physical Properties

Four petrophysical units are identified at Site U1504 according to variations in the core physical properties. Core material in PP Units 1 and 2 both consist of soft sediments. In general, with respect to PP Unit 2, Unit 1 has a higher average of NGR counts (~30 versus 20 cps), a weaker color reflectance (a mean L* value of ~40 versus 50), and a lower average of GRB values (100 versus 150). These changes in physical properties between PP Units 1 and 2 correspond to a switch of sediment compositions from nannofossil-riched clay to nannofossil ooze. A general increase of bulk (from ~1.4 to 1.8 g/cm^3) and dry density (from ~0.7 to 1.2 g/cm^3) as well as a downhole decrease of porosity (from 75% to 56%) in PP Units 1 and 2 mainly indicate sediment compaction with time. The boundary between PP Units 1 and 2 is marked by a relatively rapid increase in *P*-wave velocity and bulk density as well as a rapid decrease in porosity, compared with the general trends mentioned above. This physical property boundary corresponds to an unconformity in the seismic profile and also to a hiatus confirmed by the biostratigraphic data.

The *P*-wave velocity and bulk density increases from ~3800 to 5000 m/s and from ~2.4 to 2.9 g/cm^3, respectively, within PP Unit 3, corresponding to a transition in lithology from coral-rich limestone to clast-supported limestone. Coral-enriched limestone in the upper portion of PP Unit 3 is also associated with a moderately high porosity of ~23%. PP Unit 4 is characterized by uniformly high velocities of ~5500 m/s, high bulk densities of ~2.9 g/cm^3, and low porosities of ~3%, which correspond to the epidote-chlorite schist. A large increase in both velocities and densities at the boundary between PP Units 2 and 3, and also PP Units 3 and 4, corresponds to strong reflectors in the seismic data. The gradual downhole increase in thermal conductivity values at shallow depths is likely due to progressive compaction of the sediments.