IODP Expedition 349: South China Sea Tectonics
Site U1431 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1431 (proposed site SCS-3G) is located near the relict spreading ridge where the youngest crustal magnetic anomalies are observed in the East Sub-basin of the South China Sea. A positive magnetic anomaly that runs through this site allows regional correlation of crustal age. This site is also surrounded by abyssal highs in the ocean crust and younger seamounts, whose volcanic and/or redepositional events may be recorded by sediments recovered from this site.

The primary objective at Site U1431 is to core into the oceanic basement to determine the termination age of seafloor spreading in the East Sub-basin. The thick package of sediment (~900 m) overlying basement will also provide important constraints on the evolution of the ridge and associated late-stage magmatism, deep marine sedimentary processes, and the paleoceanographic history following the termination of spreading in the South China Sea. Additionally, this site will allow for correlation of biostratigraphic, magnetostratigraphic, and radiometric ages to the observed crustal magnetic anomalies. Physical properties and paleomagnetics measurements of basement rocks will help to elucidate the cause of the distinct magnetic contrasts between the East and Southwest Sub-basins. Furthermore, this site will provide constraints on mantle source, melting, and magma crystallization processes in the latest stages of basin formation. Physical properties measurements of core samples and wireline logging measurements will provide stratigraphic information for correlation with regional seismic profiles. Microbiological sampling will explore the deep biosphere in the South China Sea to examine how sharp changes in lithology (interfaces) may affect subsurface community structure and function, as well as how post-eruption processes might have influenced past ecosystems in the South China Sea.

The planned operations at this site included one hole, with advanced piston core (APC) and extended core barrel (XCB) coring to refusal, with the use of a free-fall funnel to allow reentry with the rotary core barrel (RCB) system to deepen the hole to

~100 m into basement. Two wireline logging runs were planned: a triple combo tool string modified to include measurement of magnetic susceptibility and the Formation Microscanner (FMS) and sonic tool string.

Operations

After a 463 nmi transit from Hong Kong averaging 11.0 kt, the vessel stabilized over Site U1431 at 0640 h (UTC + 8 h) on 31 January 2014. We cored five holes at Site U1431 (SCS-3G). The original operations plan called for one hole to a depth of ~1061 mbsf, which included approximately 100 m of basement. The plan was modified during the transit to include two additional short holes for high-resolution sampling of the upper ~20 m of section. Hole U1431A was successfully cored to a depth of 28.4 mbsf and Hole U1431B to a depth of 17.0 mbsf. After the first core from Hole U1431C retrieved a split core liner and no mudline, we opted to abandon that hole, which was completed to a depth of 14.2 mbsf, and spudded Hole U1431D. Hole U1431D was cored to a depth of 617.0 mbsf when the extended core barrel (XCB) failed, leaving the cutting shoe, core catcher sub assembly, and breakoff sub in the hole. We abandoned Hole U1431D and switched to the rotary core barrel (RCB) coring system to spud Hole U1431E, which was drilled down to 507.0 mbsf, spot cored, and then cored continuously from 575.0 mbsf to the total depth at 1008.8 mbsf. After conditioning the hole for logging, two logging runs were performed. The triple combo was run to 463.0 mbsf and the FMS-sonic to 444 mbsf with two passes. The total time spent on Site U1431 was 385.7 h (16.1 days).

A total of 122 cores were collected at this site. The advanced piston corer (APC) coring system was deployed 26 times, recovering 225.61 m of core over 228.50 m of penetration (98.7% recovery). The XCB coring system was deployed 48 times, recovering 236.50 m of core over 448.10 m (52.8% recovery). The RCB coring system was deployed 48 times, recovering 243.00 m of core over 443.5 m of penetration (54.8% recovery).

Principal Results

The cored section at Site U1431 is divided into eleven lithostratigraphic units, nine sedimentary and two igneous, based mainly on a combination of Holes U1431D and U1431E. Lithostratigraphic Unit I is a 101.16 m thick Pleistocene sequence of dark greenish gray clay and silty clay. Graded silt intervals are abundant and interpreted as

turbidites. Discrete volcanic ash layers that are either mafic or felsic in composition and 0.5–5 cm thick occur throughout the unit. This unit is underlain by Unit II of Pliocene–Pleistocene age, which is divided into Subunits IIA (101.16–194.95 mbsf) and IIB (194.95–267.82 mbsf). The 166.66 m of Unit II is dominated by dark greenish gray clay with fewer volcanic tephra layers than Unit I. Subunit IIA is characterized by the presence of clay with nannofossils and calcareous turbidites, which are not found in Subunit IIB. Rare, thin silt turbidites are largely limited to Subunit IIB. Unit III (267.82–326.12 mbsf) is a 58.30 m thick upper Miocene to Pliocene sequence of dark greenish gray clay with modest amounts of interbedded calcareous turbidites. These graded turbidites typically have sandy foraminifer-rich intervals at the base and are interpreted to represent mass wasting events from neighboring seamounts. Unit IV (326.12–412.42 mbsf) is an upper Miocene unit comprising 86.30 m of dark greenish gray clay and silty clay with minor amounts of silt and fine sand interbeds interpreted as turbidites. This unit is much reduced in carbonate content compared to overlying Unit III. Unit V (412.42–603.42 mbsf) is a 191 m thick sequence of upper Miocene dark greenish gray silty sand and interbedded clay with nannofossil ooze. Recovery is low throughout the section, but sandy core catcher samples suggest that many of the non-recovered intervals may consist of sand.

Unit VI (603.42–797.30 mbsf) is readily distinguished from the overlying units by the abundance of greenish black volcaniclastic breccia and sandstone interbedded with minor amounts of claystone. This unit is 193.88 m thick and dated to the late Miocene. The clasts in these breccias are primarily composed of highly vesicular basalt and non-vesicular to sparsely vesicular basalt, with lesser amounts of pumice and mudstone. Major element data indicate that these clasts are characteristic of ocean island basalts (OIBs). The breccia beds are typically massive and have erosive bases, indicative of deposition by mass wasting either as debris or grain flows. Based on the composition of the clasts, these deposits are likely sourced from the nearby seamounts. Unit VII (797.30–885.25 mbsf) is 87.95 m thick and middle to late Miocene in age. It is composed of interbedded dark greenish gray sandstone with lesser amounts of siltstone and claystone in a turbidite sequence. It is essentially a less coarse-grained equivalent to Unit VI and coarsens up through the unit. Unit VIII (885.25–889.88 mbsf) is a 4.63 m thick middle Miocene sequence of massive, dark olive brown claystone, which directly overlies the basalt of Unit IX (889.88–962.51 mbsf).

The mudstone represents deep marine sedimentation. Unit X (962.51–972.00 mbsf) is a 9.49 m thick sequence of lower Miocene yellowish brown claystone and claystone breccia that lies within the volcanic sequence. These sediments are underlain by the basalt of Unit XI (972.00–1007.89 mbsf).

Calcareous nannofossils, planktonic foraminifers, and radiolarians recovered at Site U1431 are typical of low-latitude assemblages, characterized by species widely found in the tropical western Pacific region. Calcareous nannofossils are generally poorly preserved and frequent or common in Units I–IV but rare or absent downhole. Planktonic foraminifers are also poorly preserved and vary from frequent to rare in Units I–IV, but absent more frequently in samples from deeper units. Radiolarians are common and well preserved in samples from the uppermost 30 m, absent from 30 to 870 mbsf, and present but poorly preserved in Units VIII and X.

The biostratigraphy of Site U1431 is based on analysis of calcareous nannofossil, planktonic foraminifer, and radiolarian assemblages in all core catcher samples and additional samples from within cores from Holes U1431D and U1431E. The sedimentary succession recovered at Site U1431 spans the lower Miocene through Pleistocene. Sediments from Units I–VIII are assigned to middle Miocene to Pleistocene calcareous nannofossil Zones NN6 to NN21 and planktonic foraminifer Zones M9 to Pt1, with no obvious hiatuses. The Pliocene/Pleistocene boundary is located between Cores U1431D-15H and -18H and the Miocene/Pliocene boundary between Cores U1431D-31X and -33X. Biostratigraphic control for the upper Miocene section is hampered by a paucity of nannofossils and planktonic foraminifers and poor core recovery in Units IV and V, which are dominated by turbidites. Nevertheless, the middle/late Miocene boundary is placed between Cores 349-U1431E-27R and -33R. In situ calcareous microfossils are absent in the claystones of Unit X; however, radiolarian biostratigraphy indicates that the rocks are early Miocene in age (approximately 16.7–17.5 Ma), corresponding to radiolarian Zone RN4. Sedimentation rates varied from ~8 cm/k.y. in the middle to early late Miocene, ~14 cm/k.y. for the remainder of the late Miocene, to ~5 cm/k.y. in the Pliocene–Pleistocene. Extremely low sedimentation rates (<2 cm/k.y.) occurred in the early to earliest middle Miocene, during deposition of the claystones of Units VIII and X.

The basalts of Unit IX were encountered at ~890 mbsf in Hole U1431E. Coring

continued to ~1008 mbsf, recovering basement basalts separated by an interflow claystone between 3.7 and 9.5 m thick at 962.3 mbsf. In total, 46.2 m of basalt was recovered over a cored interval of 108.4 m, yielding an average recovery of 42.6%. The basalts are mainly comprised of massive lava flows (six in Unit IX and two in Unit XI) up to ~26.7 m in thickness, with limited evidence for pillow basalt flows in between. Since no contacts between flow units were recovered, boundary locations and unit thickness estimates are approximate. The interpretation of igneous lithologic Units 1, 7–10, and 12 as pillow basalts is uncertain and is based on scarce evidence, such as the presence of glassy (curved) chilled margins and a single occurrence of a hyaloclastite breccia.

Most basalts at Site U1431 are aphyric and range in grain size from microcrystalline to fine-grained, with the groundmass grain size getting coarser (up to 0.7–1 mm) in the cores of the thickest massive lava flows. All basalts have a phase assemblage of plagioclase and clinopyroxene (± olivine) in their groundmass, with 0.1–0.5 mm subhedral-euhedral olivine microphenocrysts present in some lithologic units. This resembles typical mid-ocean ridge basalt (MORB) crystallization history and, in conjunction with geochemical evidence, indicates that the basalt recovered at Site U1431 is representative of typical MORB.

The alteration style of the basalts at Site U1431 is typical of MORB. Alteration color is dominated by gray to dark gray green and yellow to red brown. Typical secondary minerals include saponite, iron oxyhydroxides, carbonate, and celadonite, which represent alteration assemblages at low temperature. Alteration intensity varies from slight to complete, but the majority of the recovered basement rocks are moderately altered. There is no systematic change in the alteration nature (e.g., alteration color) with depth that might indicate a transition from more oxidizing to reducing conditions. The strongest alteration occurs in halos flanking veins, which overprints the background pervasive alteration, indicating that the overall distribution of alteration was controlled by fractures and vein structures. Most lithologic basement units include intervals with slight alteration, preserving remarkably fresh olivine crystals that show only limited alteration along their rims and “maschen” fractures.

Fractures and veins occur throughout the basalts in Hole U1431E. These features are randomly oriented, with no obvious offset or thickness variation. A fracture with

approximately 1 cm of normal offset occurs in the interflow claystone of Unit X. The basalt fractures likely formed during cooling of the lava, whereas the fractures in the interflow claystone suggest weak movement as the lava of Unit IX flowed over it. The major veins are white or reddish brown and filled with carbonate and iron oxides. Arched veins generally occur in sets, often in combination with linear veins, forming a vein network consistent with fractures formed during cooling.

Geochemistry measurements at Site U1431 aimed to characterize the interstitial water chemistry, total organic carbon (TOC), bulk carbonate content, and igneous basement rocks. The depth profiles of major elements and nutrients indicate that organic matter diagenesis, biogenic carbonate dissolution and recrystallization, and volcanic ash alteration occurred in the sediments. The interstitial waters never reach complete sulfate reduction in Hole U1431D, with minimum concentrations of ~2.3 mM occurring from ~170 to 260 mbsf. This is consistent with the very low methane concentrations, which range from 1.6 to 4.8 ppmv. Sulfate concentrations gradually increase below 260 mbsf, reaching 24.0 mM at the bottom of Hole U1431D (~600 mbsf). Shore-based isotopic analysis of these interstitial water samples should constrain the source of the sulfate-bearing fluid in Hole U1431D.

Bulk carbonate content varies with depth, ranging from 0 to 47 wt% in Hole U1431D and from 0 to 57 wt% in Hole U1431E. The discrete intervals with higher carbonate content in Hole U1431D correspond to nannofossil ooze beds, whereas in Hole U1431E higher carbonate content is associated with diagenetic carbonate concretions visible in the cores. The TOC varies from 0 to 4.7 wt% in Hole U1431D, whereas in Hole U1431E the TOC was lower and ranges from 0 to 0.74 wt%. The TOC to total nitrogen (C/N) ratio is generally less than 4 at Site U1431, indicating that the TOC is derived from a marine source; however, C/N ratios range from 8 to 12 in some intervals of lithostratigraphic Units III and IV in Hole U1431D, which could indicate a mixture of marine and terrestrial organic matter sources.

The major and minor element concentrations measured by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) on the Hole U1431D sediments indicate that they are derived from intermediate igneous or quartz-rich sedimentary sources. The basalts recovered from below ~890 mbsf in Hole U1431E have high loss on ignition (LOI) values (0.46–2.85 wt%), but low K_2O (≤0.53 wt%) and TiO_2 (1.01–

1.77 wt%). The basalt samples of Unit IX contain higher MgO, FeO, and Ni concentrations than those of Unit XI due to olivine accumulation. The basalts are mid-ocean ridge tholeiites, whereas clasts from the volcaniclastic breccias that contain high K_2O (1.08–2.67 wt%) and TiO_2 (2.10–3.13 wt%) are alkali basalts probably sourced from the nearby seamounts.

A total of 105 whole-round samples (5–10 in length) were collected for microbiological studies from Site U1431. These samples were typically taken adjacent to interstitial water whole-round samples for comparison to interstitial water chemistry when possible. These samples will be analyzed for microbial content based on DNA and lipid properties of the cells present. Subsamples were prepared for fluorescent in situ hybridization (FISH) and single cell genomics. DNA and lipid samples were preserved at –80°C, whereas FISH samples were preserved at –20°C. Four basalt whole-round samples were selected for cultivation-based studies, with sampled material inoculated into a seawater-based medium containing olivine as a source of energy. An additional 76 samples were collected and prepared for investigation of the microbiology of interfaces using lipid and nucleic acid analyses. These samples were collected mostly in the upper 200 m of Hole U1431D from specific interfaces, including five ash/clay interfaces and ten turbidite/clay interfaces. Selection of these samples was dependent upon recognition of key intervals by the core description team and occurred through consultation between the microbiologists and sedimentologists or petrologists.

Microbiology contamination testing at Site U1431 included the use of perfluorocarbon tracers (PFTs), fluorescent microspheres, and fluid community tracers. PFTs were added to the drilling fluid for all APC coring at Holes U1431B, U1431C, and U1431D, as well as for the first four XCB cores in Hole U1431D. Twelve samples were taken from six sediment cores collected over this interval to measure contamination with the PFTs. Microspheres were added to the core catcher before the core barrel was deployed in Hole U1431E over the interval from 651.8 to 952.6 mbsf. Two microsphere samples were collected from each core, one from scraping of the core surface and one as a subsample from the interior of each whole round sample. In addition, fluid community tracer samples were collected from the drilling fluids on a daily basis (for a total of 14) to track the microbial communities

typical of seawater and other drilling mud constituents. Microbial community DNA and lipids from these fluids will be compared to those measurements made on the core samples to determine if there are microbes that can be recognized as contaminant taxa.

Variations in the natural remanent magnetization (NRM) intensity at Site U1431 are generally correlated with lithology. Paleomagnetic measurements indicate that the silty clay and clayey silt in Unit I (0–101.16 mbsf) has a mean NRM intensity on the order of 3×10^{-2} A/m, whereas the clay with nanofossils in Unit II (101.16–267.82 mbsf) has somewhat higher NRM intensity (~6×10^{-2} A/m). Many discrete peaks of higher NRM values that appear in some depth intervals in both Units I and II can be tied directly to the presence of volcanic tephra layers. Magnetic susceptibility data also show positive peaks at these intervals. Overall, magnetic susceptibility and NRM intensity variations through sedimentary units are closely correlated.

Magnetostratigraphic records at Site U1431 indicate the presence of several relatively well-defined polarity intervals in the cores. Based on inclination and declination data, the Brunhes/Matuyama Chron boundary (0.781 Ma) is confidently placed at ~46 mbsf in Hole U1431D. The Matuyama Chron is defined between ~46 mbsf and ~135 mbsf. Below ~170 mbsf, the XCB cores are strongly overprinted by a drilling-induced remagnetization that cannot be removed by shipboard thermal demagnetization. The magnetic record improved in the RCB cores of Hole U1431E, allowing tentative correlation of certain parts of the magnetic polarity interval with the geomagnetic polarity timescale in conjunction with biostratigraphic constraints. In particular, the polarity shift from normal to reversed at ~716 mbsf may correspond to the C5n/C5r boundary (11.056 Ma).

For basement rock units, the observed paleomagnetic signals cannot be directly linked to the geomagnetic polarity timescale yet, because of the intermittent eruption nature of the basalts in lithostratigraphic Units IX and XI and apparently extremely low sedimentation rate for the pelagic clay sediments in lithostratigraphic Units VIII and X. Nevertheless, reliable normal and reverse polarities occur within this interval, which indicates that the eruption of the basalt units may have spanned a significant amount of time on the order of a few thousand to one million years.

Cores from Holes U1431A to U1431C were measured for *P*-wave velocity, bulk density, magnetic susceptibility (MS), and natural gamma radiation (NGR) on whole-round cores. For Holes U1431D and U1431E, measurements were also made on whole-round cores, with additional measurements on split cores and discrete samples, including thermal conductivity, porosity, and bulk, dry, and grain densities. In general, the physical properties correlate with lithology, composition, and induration. In Hole U1431D, the bulk density, *P*-wave velocity, shear strength, NGR, and thermal conductivity increase gradually with depth over the first 150 mbsf, whereas the porosity measured on discrete samples decreases from 84% to 50% in the same depth range. This indicates that sediment compaction dominates the physical properties variations above 150 mbsf. Volcanic ash layers in Unit I (e.g., at 25 mbsf and 100 mbsf) show relatively high magnetic susceptibility (300–500 SI unit) values. Below 150 mbsf, a decrease in shear strength may be associated with a larger abundance of clay. NGR counts are relatively high from the seafloor to 500 mbsf, consistent with the dominance of clay and silt in Units I–V.

Most physical properties show a significant change at about 550–600 mbsf, near the boundary between Units V and VI. *P*-wave velocity and porosity increase, whereas NGR values and thermal conductivity are relatively low, a pattern consistent with the dominance of volcaniclastic breccia and sandstone in Unit VI. Layers with higher NGR counts and high MS values occur at ~660 and ~710 mbsf. These do not correlate with the breccias, but correspond to a silt- and/or sandstone probably enriched in magnetic minerals such as magnetite. The basaltic units below 889.88 mbsf (Units IX and XI) display the lowest NGR, highest MS, and largest bulk density values. The interflow clay (Unit X) between the two basaltic units shows NGR values about 20 times larger than those of the basalts, as well as much lower MS. Lower MS and NGR values at the top of the basalt are consistent with moderate alteration in these basement units.

Two downhole logging tool strings were run in Hole U1431E, the triple combo (NGR, porosity, density, electrical resistivity, and MS) and the FMS-sonic (NGR, sonic velocity, and electrical resistivity images). The triple combo reached 464 mbsf before a bridge prevented access to the lower part of the borehole. The hole was wider than 17 inches below ~300 mbsf and had closely spaced variations in borehole width

above that depth. These were not ideal conditions for borehole log quality; however, stratigraphic changes are apparent in the natural gamma radiation and magnetic susceptibility logs. The FMS-sonic tool string reached 444 mbsf, with two passes made above that depth. Downhole temperature measurements of the borehole fluid are consistent with the low geothermal gradient (~15ºC/km) established from the advanced piston corer temperature tool (APCT-3) measurements taken on Cores 349-U1431D-4H, -7H, -10H, and -13H.