IODP Expedition 349: South China Sea Tectonics

Site U1433 Summary

Background and Objectives

Due to the marked contrast in magnetic anomaly amplitudes between the Southwest and East Sub-basins of the South China Sea (Yao, 1995; Jin et al., 2002; Li et al., 2007, 2008), it is justifiable to question whether rifting and drifting within these two sub-basins were synchronous or diachronous and how these sub-basins evolved in comparison to the Northwest Sub-basin. Site U1433 (proposed site SCS-4B) is located in the Southwest Sub-basin near the relict spreading center and magnetic anomaly C5d identified by Briais et al. (1993). Together with Site U1431 in the East Sub-basin, coring at Site U1433 should help to explain the sharp differences in magnetic amplitude between the East and Southwest Sub-basins and test the hypothesis that in the Southwest Sub-basin the breakup from continental rifting to seafloor spreading occurred more recently than in the East Sub-basin (Pautot et al., 1986). Coring will help determine the age of this sub-basin near the end of the spreading and correlate ages from magnetic anomalies with biostratigraphic, magnetostratigraphic, and radiometric ages. The apparent weak magnetization in basement rocks (Li et al., 2008) will be examined via petrological analyses of chemical compositions and measurements of magnetic susceptibility. The specific objectives at this site are to:

1) Determine the termination age of spreading in the Southwest Sub-basin and correlate it to ages of regional tectonic events;

2) Test the hypothesis that the Southwest Sub-basin evolved within continental lithosphere by rifting and subsequent seafloor spreading later than the East Sub-basin;

3) Measure magnetization, mineralization, and geochemical compositions of basement rocks to trace how the mantle evolved through time; and

4) Examine the paleoceanographic and sedimentary response to the opening of the South China Sea.

Operations

After a 334 nmi transit from Site U1432 averaging 11.2 kt, the vessel stabilized over Site U1433 at 0230 h (UTC + 8 h) on 8 March 2014. The original operations plan consisted of one hole to a depth of ~965 mbsf, which included 100 m of basement. This plan was modified during the transit to eliminate both the use of a free-fall funnel and the use of the extended core barrel (XCB) system by coring two holes. Hole U1433A was cored using the advanced piston corer (APC) to refusal at a depth of 188.3 mbsf. Hole U1433B was drilled down to 186.1 mbsf and then cored below that using the rotary core barrel (RCB) system. The sediment/basement interface was encountered at ~798.5 mbsf and we cored in basement to 858.5 mbsf. After conditioning the hole for logging, we deployed the modified triple combo tool string and the Formation MicroScanner (FMS)-sonic tool string to 840 m wireline depth below seafloor (WSF), with multiple passes made in the basement section of the hole with the latter tool.

A total of 94 cores were collected at this site. The APC coring system was deployed 20 times, recovering 168.79 m of core over 188.3 m of penetration (90% recovery). The RCB system drilled one 186.1 m interval, and then collected 74 cores, recovering 443.04 m of core over 672.4 m of penetration (66% recovery). The overall recovery at Site U1433 was 71%. The total time spent on Site U1433 was 284.5 h (11.85 days).

Principal Results

The cored section at Site U1433 is divided into four lithostratigraphic units (three sedimentary and one igneous) based on a combination of Holes U1433A and U1433B. Lithostratigraphic Unit I is a 244.15 m thick sequence of Pleistocene dark greenish gray clay, silty clay, and clay with nannofossils. The clay is interbedded with small volumes of generally thin, graded quartzose silt and nannofossil ooze, both interpreted to be turbidite deposits that comprise <5% of the unit. This unit is underlain by Pleistocene to middle Miocene Unit II (244.15–747.93 mbsf). This unit is divided into two subunits: IIA (244.15–551.32 mbsf) and IIB (551.32–747.93 mbsf). The entire unit is 503.78 m thick and dominated by dark greenish gray clay with frequent graded carbonate interbeds, largely comprised of nannofossil ooze and chalk that are characterized by sharp, erosive bases and gradational, bioturbated tops. In Subunit IIB carbonate beds are occasionally substantially thicker, up to several meters, rather than <1 m, and usually <50 cm, in Subunit IIA. The carbonates are turbidite deposits with evidence of re-sedimentation from shallow-water regions based on the occurrence of benthic foraminifers that dwell in the photic zone. The lowermost sedimentary sequence, Unit III (747.93–796.67 mbsf), is a 48.74 m thick lower to middle Miocene sequence of claystone and claystone with silt. Most of the unit is a reddish brown or yellowish brown massive sediment with common burrowing stained black by diagenetic alteration. Similar to Units I and II, Unit III bioturbation is consistent with sedimentation at lower bathyal to abyssal water depths (*Nereites* ichnofacies). Unit III contains sparse, relatively thin calcareous turbidites. There is no evidence for hydrothermal influence on sedimentation or diagenesis despite the fact that it lies directly above the basalts of Unit IV (796.67–857.48 mbsf). Unit III is the product of relatively slow sedimentation in a distal setting at the foot of a continental margin and is similar to the basal sediment at Site U1431 and to "red clay" deposits from the central Pacific.

Analysis of calcareous nannofossils, planktonic foraminifers, and radiolarians in core catcher samples and additional samples from split cores indicates that the sedimentary succession recovered at Site U1433 spans the lower Miocene to the Pleistocene. Age control for the lower to lower middle Miocene section is difficult because of very rare occurrences of microfossils in the brown claystones (Unit III) overlying the basement. Nannofossils in sediments preserved in and around basalt pillows are Oligocene to early Miocene in age, but additional post-expedition analyses are required to determine if these assemblages are reworked or in situ.

Calcareous nannofossils are generally common to abundant with good preservation in samples from the Pleistocene–Pliocene section, but are rare and heavily overgrown or even barren in some Pliocene and upper Miocene samples, especially those from nannofossil ooze/chalk intervals. Planktonic foraminifers also show considerable variations in both abundance and preservation. They are abundant and well preserved in silty layers with numerous small (<150 μm) specimens, but poorly preserved and very difficult to identify in lithified intervals. Radiolarians are abundant and well preserved in the upper Pleistocene section in Hole U1433A, becoming rare or absent in older sediment sections downhole. In Hole U1433B, samples are barren of radiolarians until the brown claystone of Unit III, in which rare and poorly preserved but biostratigraphically significant specimens occur.

Integration of biohorizons and paleomagnetics datums allows us to estimate extremely low sedimentation rates (<0.5 cm/k.y.) during the early to middle Miocene. Sedimentation rates varied from ~5 to 9 cm/k.y. from the late Miocene to early Pleistocene, but then increased sharply to ~20 cm/k.y. since 1 Ma.

We cored 60.81 m into igneous basement below 796.67 mbsf in Hole U1433B, recovering 29.02 m of basalt (48% recovery). This short basement succession was divided into 45 igneous lithologic units, which are grouped into lithostratigraphic Unit IV, and is immediately overlain by hemipelagic dark reddish brown claystone (Unit III). The basement is comprised of a 37.5 m thick succession of small pillow basalt lava flows in the top, followed by a 23.3 m series of massive basalt lava flows toward the bottom.

The igneous basement begins with a sequence of sparsely to highly plagioclase-phyric pillow basalt with a trace of olivine microphenocrysts. Most of the pillow basalts are non-vesicular to sparsely vesicular, range in grain size from crypto- to microcrystalline, and in many cases have well-preserved glassy chilled margins along both the top and bottom unit boundaries. A few larger lobate flows are present, with flow thicknesses varying between 0.1 and 1.1 m. In two intervals, inter-pillow hyaloclastite breccias were encountered, with remnants of baked limestone in which Oligocene to early Miocene nannofossils occur. In between these sequences of pillow basalt flows, one 5.2 m thick microcrystalline to fine-grained massive flow was encountered that is sparsely olivine-plagioclase-phyric, but has a holocrystalline groundmass with abundant clinopyroxene present in the interstitial spaces. Downhole the basement is characterized by more massive basalt lava flows up to ~12.8 m in thickness. These massive flows have similar petrologic characteristics and range from sparsely to highly plagioclase-phyric with minor microphenocrysts of olivine. Toward the interiors of the thickest lava flows the grain size increases to fine grained.

All basalts have a phenocryst phase assemblage of plagioclase ± olivine, whereas the more massive flows also have clinopyroxene in their groundmass. This assemblage resembles a typical mid-ocean ridge basalt (MORB) crystallization assemblage and, in conjunction with geochemical evidence, we conclude that the basement basalt at Site U1433 is typical MORB.

Alteration is also typical of that of MORB. The basalt ranges from mostly fresh/less altered to moderately altered in intensity, typically as halos in association with cracks and veins, and from gray to dark gray green and yellow to red brown in color. The background of the basement basalt is mostly fresh to slightly altered, and most alteration occurs near the veins as halos. Basalt glasses are most abundant near the quenched margin of lava flows and are commonly altered to greenish palagonite, which might indicate alteration from more reducing fluids than that of brownish palagonite. Alteration veins are abundant at the top of the basement cores and decrease with depth, indicating limited downwelling fluid flow, which is also consistent with fewer fractures that occur with increasing depth. Vein filling minerals include carbonate, celadonite, Fe-oxide/hydroxides, saponite, smectite, quartz, and some blue minerals that are difficult to identify. Typical secondary minerals include saponite, Fe-oxides, carbonate, and celadonite, which represent a low temperature alteration assemblage.

We measured 240 fractures and veins in the basalt of Hole U1433B. Most of the fractures occur along existing veins without either obvious offset or striations on the surfaces, indicative of drilling-induced fractures, whereas natural fractures are quite rare. In general, the veins can be separated into four types with different shapes: single linear, triple-junction, branched, and crosscutting. Arched, crosscutting, and triple-junction veins are usually distributed in pillow basalt layers, whereas single linear, branched, or sinuous veins are usually in the massive flows. The highest frequency of veins occurs in the pillow basalts, whereas there are fewer veins within the massive flows. Alteration along fractures and veins produced 1–2 cm wide yellow- to brown-colored halos.

At Site U1433, interstitial water sulfate concentration decreases with depth and sulfate is almost completely consumed (<1 mM) below ~30 mbsf. Alkalinity increases with depth, reaching a maximum of 25.8 mM at ~30 mbsf, before gradually decreasing with depth. The depth at which sulfate is consumed and alkalinity reaches its peak corresponds to an increase in methane from ~3 to 1100 ppmv. Below this depth, methane varies between approximately 22,000 and 93,000 ppmv, before it decreases significantly below ~590 mbsf. Ethane and other higher hydrocarbons are also present in low concentrations below ~60 mbsf. This indicates that anaerobic oxidation of methane coupled with sulfate reduction is ongoing in the sediments. Other interstitial water chemistry profiles reflect both lithologic changes and diagenetic processes. Total organic carbon (TOC) varies from 0 to 1.0 wt%, with a general decrease downhole. $CaCO_3$ content ranges from 0.5 to 77.8 wt%, with the lowest values (generally <15 wt%) in the upper 300 m of the site. Intervals with higher $CaCO_3$ content below 300 mbsf correspond to carbonate turbidite layers in lithostratigraphic Unit II. Peaks in TOC and the total organic carbon to total nitrogen (C/N) ratio at ~450 mbsf and 540–590 mbsf could reflect an influx of terrestrial organic matter; however, additional shore-based work is needed to confirm this interpretation.

At Site U1433 we collected fifty whole-round samples for microbiological analysis from the seafloor to 790 mbsf. When possible, these samples were collected adjacent to samples for interstitial water measurements. We also collected 164 samples from split cores to study the microbiology of interfaces or coring induced disturbance. We obtained these samples from 4 to 154 mbsf in Hole U1433A and from 187 to 854 mbsf in Hole U1433B. Most of the samples collected were preserved for shore-based analysis of DNA, RNA, and lipids. Some portions of the whole-round samples were selected for cultivation-based studies to enrich for anaerobic autotrophs and heterotrophs.

We used three methods of contamination testing during coring at Site U1433: perfluorocarbon tracers (PFTs), microspheres, and fluid community tracers (FCTs). PFT samples were acquired from the outside and inside of 16 cores between 140 and 390 mbsf in Holes U1433A and U1433B. PFTs were not detected in most of the samples collected and analyzed for this tracer regardless of whether the samples were taken from the outside or the inside of the core. Microsphere tracers were used with the RCB coring system in Hole U1433B between 709 to 854 mbsf. Two microsphere samples were taken from each core collected between these depths: one from scrapings of the core surface and one as a subsample from the interior of each whole-round sample. Twenty-four FCT samples were collected either from the drilling fluids that drained from the core liners when cores arrived on the catwalk or from a sampling port near the mud pumps on the rig floor during active coring. The fluids collected for FCT samples correspond to cores obtained from depths ranging between 6 and 824 mbsf.

We conducted paleomagnetic studies at Site U1433 on both sediment and basement cores using pass-through magnetometer measurements on all archive half sections and alternating field (AF) demagnetization on representative discrete samples. Magnetostratigraphic records at Site U1433 suggest the existence of eight short reversed polarity events within the Brunhes normal chron. These short-lived events most likely represent geomagnetic excursions as both declination and inclination change. The polarity shifts at depths of ~12, 18, 28, 48, 53, 132, and 152 mbsf match well with known excursion events: Mono Lake (33 ka), Laschamp (41 ka), Blake (120 ka), Iceland Basin (180 ka), Pringle Falls (211 ka), Big Lost (560–580 ka), and Stage 17 (670 ka). For two directional anomalies at depths of ~78 and 88 mbsf, there are no counterparts from previous studies and further shore-based work is needed to confirm the origin of these two anomalies. The Brunhes/Matuyama boundary is tentatively placed at ~188 mbsf in Core U1433A-20H, which indicates a higher sedimentation rate (~23.7 cm/k.y.) for the Middle–Late Pleistocene compared to Sites U1431 and U1432. Such a high sedimentation rate facilitates preservation of the short-lived polarity excursions mentioned above.

In Hole U1433B, six major positive chrons are recognized and tied to the geomagnetic polarity timescale using constraints from biostratigraphy. The basal boundaries for the Matuyama chron (2.581 Ma), Gauss chron (3.596 Ma), and Gilbert chron (6.066 Ma) are placed at ~350 mbsf, 420 mbsf, and 550 mbsf, respectively. The basal age for sediments in Core U1433B-60R is ~11 Ma. Paleomagnetic results for the basalt units show that the upper part of the basement (805–817 mbsf) is dominated by positive polarity. Between ~817–830 mbsf, a relatively well-defined reversed polarity zone is observed. Below this depth range, the paleomagnetic inclinations display both normal and reversed polarities. Overall, the remanent magnetization of rocks below ~817 mbsf is dominated by reversed polarity. Such a pattern can be generally correlated to the upper part of the basalt units for Site U1431.

Cores from Holes U1433A and U1433B were measured for physical properties on whole-round cores, split cores, and discrete samples. The physical properties correlate well with lithology, composition, and observed lithification. The bulk density, *P*-wave velocity, shear strength, natural gamma radiation (NGR), and thermal conductivity increase gradually with depth over the first 150 mbsf, whereas the porosity measured on discrete samples decreases from 90% to 50% over the same depth range. This indicates that sediment compaction dominates physical property variations above 150 mbsf. Below 240 mbsf, variability in porosity, magnetic susceptibility (MS), and NGR values reflects interbedding of carbonate and clay layers. An increase in *P*-wave velocity from ~1700 to

~2000 m/s near 550 mbsf coincides with stronger lithification in the deeper sediments. From 680 to 750 mbsf, *P*-wave velocities measured in the lithified carbonates reach ~2600 m/s, showing a strong contrast with those measured in the clay (~2000 m/s). The strong reflectors observed in the seismic profile from this site probably result from this contrast in velocity. The clays from 750 to 800 mbsf show a gradual increase in MS and decrease in NGR. The basalts below 800 mbsf display very low NGR and porosity, and variable MS. Some of the fresh, phenocryst-rich basalts have very high MS and *P*-wave velocities.

The modified triple combo and FMS-sonic tool strings were run in Hole U1433B. Both tool strings reached 840 m WSF, about 18 m short of the bottom of the hole. Between 100–550 m WSF, there were rapid variations in borehole diameter from ~25 cm to wider than 43 cm. Below 550 m WSF, the hole diameter tended to be in gauge, with fewer washed out zones. There is a trend of increasing density and sonic velocity from the top of the logs at 100 m WSF down to 750 m WSF due to compaction and cementation with depth. Superimposed on this trend, excursions to higher velocity and photoelectric factor (PEF) and to lower NGR mark the occurrence of carbonate beds. This information was used to infer lithology in the unrecovered intervals of Hole U1433B. In the red clay of Unit III, from ~750 to 800 m WSF, high values in the PEF log indicate that hematite and other oxides increase in concentration downhole toward the top of the basalt at ~800 m WSF. Pillow basalt, a massive basalt flow, fractures, and veins are seen in the FMS images in the basement.

References

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