IODP Expedition 356: Indonesian Throughflow
Site U1464 Summary

Background and Objectives

At 270 m water depth, Site U1464 is currently in an outer ramp setting (James et al. 2004), approximately 50 km southeast of the Rowley Shoals. The seabed in the vicinity of the site is a poorly-sorted, carbonate-rich (>90%) sediment made up of bioclastic gravel, sand, and mud (Jones, 1973; James et al., 2004). Site U1464 is 5 km up dip from a drowned "fossil" reef/shoal described by Jones (1973) and Ryan et al. (2009) and connected to the site by parallel, laterally persistent seismic reflectors; therefore, improved ages for these reflectors may allow us to date the initiation and demise of this reef/shoal. The proximity of Site U1464 to a previously identified drowned shoal makes this site unique and significant: stratigraphic data and paleobathymetric determinations obtained will allow robust estimates of the subsidence history of this part of the NWS and its role in carbonate platform drowning. As the most northern site of the Expedition 356 coring transect, the sediment and biota at Site U1464 are likely to record strong Western Pacific Warm Pool and ITF signals vital to understanding the history of these important oceanic features. The strata of this site were also targeted for a Plio–Pleistocene record of the Australian monsoon and aridity.

Operations

The original plan for Site U1464 was to core four holes: three APC holes to refusal, with the last two holes being extended to 600 m or refusal with the XCB system. The final hole would have been a deep hole to total depth (840 mbsf) cored with the RCB system. However, we began the first hole (U1464A) with the XCB system to ensure that the surface sediments were suitable for piston coring. After two cores, we determined that the APC system would be appropriate. The second hole (U1464B) was piston cored with both the APC and HLAPC systems to 316.9 mbsf. After completing the piston coring to refusal, we decided to core the deep hole with the RCB system next. Subsequently, this allowed us to accurately allocate time for the remainder of the site. Hole U1464C was drilled without coring to 308.0 mbsf and then RCB cored to a final depth of 840.0 mbsf. The hole was conditioned for logging and the bit was dropped to the bottom of the hole. While pulling the drill string to logging depth (86.88 mbsf), the hole was displaced with heavy mud from 363.1 mbsf to the seafloor. The triple combination tool string was

assembled and deployed. The tool string performed a downlog to 783.7 m WSF, 56.3 m from the total depth of Hole U1464C. While logging up with the calipers open, the hole collapsed, trapping the tool string at 619.1 m WSF. The triple combination was successfully recovered after lowering the open-ended drill pipe down the hole, over the wireline, and eventually over the tool string. The tool string was then slowly pulled up to the rig floor using T-bars on the wireline. During recovery of the logging tool string, we had to stop rotating the drill string; as a result it became stuck in the hole. It was recovered with overpull, rotation, and pumping, and the drill string was then recovered on the rig floor. With over 2 d of operational time remaining, the APC/XCB coring system was reassembled and Hole U1464D was started. We first used the APC system to core to 293.5 mbsf. All APC cores were oriented and six formation temperature measurements were taken. After reaching piston coring refusal, we switched to the XCB system and cored to a final depth of 529.6 mbsf. The last core was on deck at 1410 h on 26 September. The drill string was pulled back to the rig floor and secured, ending coring operations on Expedition 356 at 2100 h on 26 September. The total time spent on Site U1464 was 185.25 h (7.7 d).

The overall recovery for Site U1464 was 49% and the totals for each coring system were as follows:

- APC: 606.7 m cored, 554.41 m recovered (91%)
- HLAPC: 3.7 m cored, 3.75 m recovered (101%)
- XCB: 255.5 m cored, 34.85 m recovered (14%)
- RCB: 532.0 m cored, 94.03 m recovered (18%).

Principal Results

Lithostratigraphy

The lithostratigraphy of Site U1464 is divided into five units. The unit boundaries were defined using visual core description, smear slide observations, NGR data, XRD, and thin section analyses from Holes U1464B, U1464C, and U1464D.

Unit I (0–44.10 mbsf (Hole U1464B); 0–43.00 mbsf (Hole U1464D)) is 43–44 m thick and consists of unlithified, creamy-gray sediments with coarse silt- to fine sand-sized peloids in varying abundances, with the last occurrence of peloids marking the base of the unit. The sediment is composed of mainly skeletal grainstone in the upper part,

mudstone dominating the middle and lower part of the unit, and short intercalated packstone and wackestone intervals. The generally low siliciclastic content of the unit is dominated by mica with minor amounts of quartz. The unit contains abundant foraminifers and pteropods with some macrofossils (e.g., scaphopods, bivalves, and solitary corals).

Unit II (44.10–138.20 mbsf (Hole U1464B); 43.0–140.39 mbsf (Hole U1464D)) is ~95 m thick and consists mainly of unlithified, homogeneous wackestone that includes a packstone interval and a relatively high abundance of authigenic glauconite and glauconitized microfossils. The top of the unit is defined by the loss of peloids as a common sedimentary component. Macrofossils are sparse and concentrated in coarser-grained intervals. Bioturbation is slight to moderate throughout the unit. Disseminated pyrite grains are common in the lower part of the unit along with occasional pyrite nodules and celestite concretions. Siliciclastic content generally increases but is variable, particularly in the lower half of the unit.

Unit III (138.20–308.86 mbsf (Hole U1464B); 140.39–308.74 mbsf (Hole U1464D)) is ~170 m thick, with the top of the unit marked by a transition from wackestone to mudstone and by a decrease in sand-sized siliciclastic content and an increase in clay-sized sediment. Overall siliciclastic content is very fine grained in Unit III, with a near absence of coarse-grained material. The unit consists mainly of unlithified, grayish-green to greenish-gray homogeneous mudstone with moderate bioturbation and common disseminated pyrite and pyrite concretions. Macroscopic bioclasts are very sparse but microfossils are abundant and well-preserved with a marked increase in calcareous nannofossils noted in smear slides.

Unit IV (308.86–316.95 mbsf (Hole U1464B); 308.00–521.40 mbsf (U1464C); 308.74–523.97 mbsf (Hole U1464D)) is ~215 m thick and marked by a transition to dolomitic packstone. The unit consists of three main intervals of dolomitic limestone separated by two intervals of skeletal limestones. Gypsum nodules are common in the dolomitic intervals and commonly co-occur with anhydrite nodules in the lower 46 m of the unit. Karstic surfaces, cavities, and moldic porosity are also common, especially in the skeletal limestones. Macrofossils are present and diverse in both lithologies, often occurring as molds. Bioclasts include many organisms typical of shallow habitats, including larger

benthic foraminifers (e.g., *Cycloclypeus*), some zooxanthellate corals, and crustose coralline algae. Siliciclastic material is generally absent in Unit IV.

Unit V (521.40–832.90 mbsf (Hole U1464C)) is 311.50 m thick and consists primarily of dolomitic limestones (mudstone, wackestone, packstone, and grainstone) and dolostone. The top of the unit is defined by the first occurrence of littoral deposits. The upper part of the unit (~100 m) contains several heavily dolomitized intervals, while the lower part (~55 m) is composed of lithified increasingly coarser packstones and grainstones. Macrofossils include fragments of molluscs, echinoid spines, bryozoa, and large benthic foraminifers. Fossil content generally decreases towards the base of the hole, while bryozoans increase in abundance and become common in the lower 10 m. Siliciclastic content continues to be generally absent to low with angular sand-sized quartz noted in the lowermost interval.

Biostratigraphy and Micropaleontology

Site U1464 yielded a complete stratigraphic succession from the early Pleistocene to late Miocene, with usually abundant and well-preserved calcareous nannofossils. The Pliocene–Pleistocene boundary (2.59 Ma; within NN16) is placed between 97.42–108.29 mbsf, and the Miocene–Pliocene boundary (5.33 Ma; within NN12) between 228.4–293.15 mbsf. The abundance and preservation of planktonic foraminifers at Site U1464 was moderate to good for the entire Pliocene–Pleistocene with common to abundant planktonic foraminifers between 2.26 and 293.2 mbsf. Biostratigraphic marker species were identified for the mid-Pleistocene boundary (0.61 Ma; Top *Globorotalia tosaensis*) at 11.51 mbsf, the Plio–Pleistocene boundary below the Top of *Globorotalia limbata* (2.39 Ma; 88.17 mbsf), *Dentoglobigerina altispira* (3.47 Ma; 126.3 mbsf) for the mid-Pliocene, and *Sphaeroidinellopsis kochi* (Top 4.53 Ma; 272.57 mbsf) for the early Pliocene. An extended interval that was barren, or contained heavily recrystallized foraminifers and very rare nannofossils, occurs below 347.08 mbsf to the bottom of Hole U1464C (832.8 mbsf) corresponding to the barren interval from 328.52 mbsf to the bottom of Hole U1464D (523.97 mbsf). The final biostratigraphic datum is a benthic foraminifer, which suggests the material in Sample U1464C-43R-2 (707.57 mbsf) is older than 12.8 Ma (Top *Nephrolepidina ferreroi* TF1-2; Renema, 2007).

Samples from Site U1464 contain between 6%–100% benthic foraminifera with *Cibicidoides* spp. as the most common taxa. Four assemblages can be identified based on

the abundance of *Textularia* spp. (Assemblage 1), *Lenticulina* spp., *Clavulina subangularis*, *Neoeponides* spp., and *Pseudorotalia* spp. (Assemblage 2), *Amphistegina* spp., *Elphidium* spp., and *Operculina* spp. (Assemblage 3), and *Cibicidoides* spp. (Assemblages 4). One to 43 species are present in the samples and the assemblages suggest paleodepths that start relatively deep (inner to outer shelf (Assemblage 1)) at the bottom of the site (~840.0 mbsf) and then deepen (outer shelf to upper bathyal (Assemblage 2)) until around 300–310 mbsf. Beginning from this depth, it rapidly shallows (inner to middle shelf (Assemblage 3)) and then deepens again (inner to outer shelf (Assemblage 4)). Preservation was affected by fragmentation, abrasion, encrustation, and infilling, and varied from very good to poor throughout the site but was most frequently good for Assemblages 1 and 2, and poor for Assemblages 3 and 4.

Geochemistry

At Site U1464, 85 samples were analyzed for headspace gas content, 20 samples (5–15 cm whole rounds) for interstitial water geochemistry measurements, and 23 samples for total organic carbon (TOC), calcium carbonate ($CaCO_3$), and total nitrogen (TN). In general, Site U1464 is characterized by the lowest concentrations of headspace gases of all of the Expedition 356 sites, with methane ranging from 0–3.2 ppmv and almost no detection of higher molecular weight hydrocarbons. Elevated salinity characterizes the site, with a value of 35 at the top, increasing gradually with depth to 105 at the bottom, and a mean value of 68. Similar to previous Sites U1462 and U1463, high salinity at Site U1464, as well as a number of elemental trends noted in the interstitial water samples, appears to be related to the presence and dissolution of anhydrite, which was observed in Lithostratigraphic Units IV and V. A number of elements exhibit increasing concentrations with depth, including sodium, chloride, barium, bromine, calcium, potassium, and sulfate. The majority of samples at this site are characterized by high $CaCO_3$ content (mean value 78.8%) and low values of TOC (mean value 0.6%) and TN (mean value 0.018%). However, there are two samples from black layers in Sections U1464C-24R-2 and U1464C-25R-2 that have extremely low calcium carbonate content (3.6% and 2.7%) but different characteristics in TOC and TN values. The sample at 523 mbsf (U1464C-24R-2) contains low TOC (0.77%) and TN (0.034%), similar to the samples from other depths. In contrast, the slightly deeper sample at 532 mbsf (in Section U1464C-25R-2) has much higher TOC (1.94%) and TN (0.079%), suggesting that,

despite appearing visually similar, these black layers represent different depositional environments.

Paleomagnetism

A total of 20 discrete samples were taken from Holes U1464B, U1464C, and U1464D. Isothermal remanent magnetism (IRM) acquisition and backfield IRM measurements were performed for four selected discrete samples (U1464B-18H-4-W, 74–76 cm; U1464B-24H-3-W, 70–72 cm; U1464C-22R-4-W, 50–52 cm; and U1464C-34R-1-W, 46–48 cm), chosen according to the observed demagnetization behaviour throughout the site. Two samples (U1464C-22R-4, 50–52 cm, and U1464C-34R-1, 46–48 cm) reached saturation IRM at ~100 mT, Sample U1464B-24H-3, 70–72 cm, saturated at ~400 mT, whereas Sample U1464B-18H-4, 74–76 cm, did not reach saturation in fields up to 1.2 T. Remanent coercivity values of the four samples ranged between 44 mT and 83 mT. Bulk susceptibility measurements were also performed on all of the discrete samples, and results ranged from $-7.95 - 110.24 \times 10^{-6}$ SI units.

Archive-half core sections from Hole U1464D were measured on the SRM to construct the magnetostratigraphy. Resulting intensity values generally ranged from 10^{-5} to 10^{-3} A/m, with exceptions between ~158–180 mbsf (Cores U1464D-18H to 22H), and ~245–293 mbsf (Cores U1464D-27H to 32H), for which intensity values reached $\sim 10^{-1}$ A/m. A persistent negative inclination trend extended from the seafloor to ~210 mbsf (Core U1464D-23H), below which there was a gradual shift towards lower inclination values, and more frequent positive inclination intervals. Magnetostratigraphic data for Hole U1464D indicate the Gauss/Gilbert boundary (3.596 Ma) at ~282 mbsf. In addition, it is possible that the C3n/C3r boundary (5.235 Ma) occurs between 272.66–277.85 mbsf because it can be constrained by a biostratigraphic datum of 5.59 Ma at 281.39 mbsf.

Physical Properties

Stratigraphic overlap between Holes U1464B, U1464C, and U1464D is confirmed by physical properties patterns, including magnetic susceptibility, natural gamma radiation, and moisture and density (MAD) results. Detailed analysis of *P*-wave velocity, as measured in sediments obtained from three different coring techniques (APC, XCB, and RCB) reveals interesting variations. *P*-wave velocities measured on XCB and APC cores form parallel trends. However, XCB *P*-wave velocities fall within two distinct velocity

ranges. The lower range is similar to *P*-wave velocities obtained on APC cores, and corresponds to the drilling-induced "slurry" between coherent portions of XCB core. A second range is ~150 m/s higher and corresponds to the cohrent pieces of XCB cores ("biscuits"). Sediments obtained during RCB coring tend to have 400–650 m/s higher velocities than those obtained during APC coring. An estimate of the geothermal heat flux of 59.1 mW/m^2 was derived from a combination of the six formation temperature estimates and core-based thermal conductivity measurements.

Downhole Logging

Downhole measurements were conducted in Hole U1464C with the triple combination tool string. The deployment of the tool string consisted of a downlog (0–783 m WMSF) and an uplog between 783–615 m WMSF. At 615 m WMSF on the uplog, the tool became stuck in the hole, and considerable effort was undertaken to retrieve the tool. As a result, no other logging tool strings were run. Wireline NGR data obtained during the downlog with the triple combo were in agreement with NGR data measured on the cores. Between 84–305 m WMSF, wireline NGR ranges between 25 and 55 gAPI and the variability in this interval is the result of variability in potassium (K) and thorium (Th), whereas the signal from uranium (U) is subdued. In the underlying interval, between 305–747 m WMSF, NGR ranges between 15 and 40 gAPI and the variability is primarily the result of variations in U, rather than variation in K or Th, both of which show generally low concentrations. Downhole magnetic susceptibility measurements were affected by temperature and were judged to be of insufficient quality for interpretation. Wireline bulk density and porosity measurements were only carried out in the interval between 764–617 m WMSF, during the uplog. The wireline bulk density measurements in this interval generally agree with data measured on core samples. In contrast, the wireline porosity measurements only agree with MAD results between 680–720 m WMSF and between 735–755 m WMSF.

Stratigraphic Correlation

Site U1464 was cored to ~840 mbsf using a combination of the APC, XCB, and RCB systems. The upper ~300 m was double cored with the APC system (Holes U1464B and U1464D) and a strong correlation was produced using the NGR data. The correlation was extended to ~320 mbsf with overlap between the APC (Hole U1464B) and XCB systems (Hole U1464D), but is less certain because of recovery gaps and biscuiting in the XCB

cores. A continuous spliced section could not be created because there were only two holes in the uppermost sections. However, sampling for most paleoceanographic studies can use the correlation, particularly since sedimentation rates are elevated (17 cm/k.y.) in the expanded early Pliocene section (180 to ~320 mbsf in Holes U1464B and U1464D).

References

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