IODP Expedition 356: Indonesian Throughflow

Site U1462 Summary

Background and Objectives

Site U1462 is 50 km north of the Montobello Islands in the northern Carnarvon Basin adjacent to (~150 m) the Fisher-1 industry well. Site U1462 is on the outer edge (87 m water depth) of a middle ramp (James et al. 2004). The seabed in the region is a carbonate-rich (>90%) gravel and sand with minor mud (Jones, 1973; James et al., 2004). Coring at Site U1462 targeted a sequence of shelfal to shelf-edge carbonates that overlie a Miocene sand unit (the Bare Formation).

The primary aim of coring Site U1462 was to obtain a record of the variation in Indonesian Throughflow (ITF) connectivity over the last 5 m.y. Previous analyses of foraminifera in 28 sidewall cores from the adjacent Fisher-1 well revealed carbonates that contain horizons of biogeographically significant Indo-Pacific foraminifera (sensu Gallagher et al., 2009), suggesting intermittent ITF connectivity. Several transported horizons containing these foraminifers are present in the Plio–Pleistocene strata cored at Site U1462. Further analyses are likely to reveal a more complete record of ITF connectivity than previously recognized. Another objective of Site U1462 was to date strata adjacent to several drowned reefs (Gallagher et al., 2014) to determine the age and environmental conditions of their onset. Facies and fossil paleoenvironmental analyses of the succession recovered will shed light on when, how, and why these reefs first developed and why they drowned. An additional aim was to obtain an interglacial Plio–Pleistocene record of the Australian monsoon. Site U1462 was closer to the shoreline during this time than Site U1461 and has yielded significantly more terrigenous material. Shore-based analyses of the pollen, clays, and other terrestrial sediments at this site will reveal a proximal Plio–Pleistocene history of the Australian monsoon. Finally, a variety of deep and shallow water carbonate facies were encountered at Site U1462. Post-expedition analyses of these strata will allow detailed estimates of Plio–Pleistocene paleobathymetry and subsidence, fulfilling another key scientific objective.

Operations

Operations at Site U1462 consisted of four holes, two of which were logged. The original plan called for three APC holes to refusal, with the last two holes being extended to refusal with the XCB system. A fourth RCB hole was planned after which the hole would be logged; however, the completion of Site U1462 differed from the initial plan with the first attempted core. Recovery of the mudline core was attempted with the HLAPC system. Unfortunately, after shooting the core into the seafloor, we were unable to retrieve the core barrel because it was bent. After pulling the bottom-hole assembly (BHA) back to the surface, we cut the core barrel out. We redeployed the BHA and Hole U1462A was cored with the XCB system to 855 mbsf (Cores U1462A-1X to 100X). There was a brief attempt to use the HLAPC system, but after one 0.25 m recovered interval, the XCB system was used exclusively to total depth. Recovery was poor (<10%) during the first 300 m of coring, but improved dramatically for the lower 555 m. After successfully coring to 855 mbsf, the hole was logged with the triple combination and Formation MicroScanner and sonic imager (FMS-sonic) tool strings. An attempt to conduct a vertical seismic profile with the Versatile Seismic Imager (VSI) was canceled because of multiple whale sightings during the protected species watch. The second hole (U1462B) was cored to 52.0 mbsf in an attempt to recover additional material in the poor recovery section of Hole U1462A. Only 1.99 m of material (4%) was recovered in Hole U1462B. After operations were completed at Hole U1462B, RCB coring was conducted in Hole U1462C. Thirty-three meters were drilled with a center bit installed. The center bit was pulled and coring with the RCB system began from 33.0 mbsf. Cores U1462C-2R to 178R were recovered to 950.0 mbsf. In order to maximize recovery for Hole U1462C, we used half-length advances (4.8 m instead of 9.7 m) while cutting cores. There were only two sections of the hole in which full advances were used (Cores U1462C-65R and 66R, and 134R to 143R). After the completion of coring, the bit was dropped and the hole was conditioned for logging. The upper ~300 m was displaced with heavy mud. All three logging tool runs were successful. The triple combination tool string recovered data from ~896–89 m WSF. The VSI tool string was deployed from 770 m WSF (where a bridge was encountered) to 107 m WSF with 10 min stations every 25 m. The FMS-sonic also reached a total depth of ~770 m WSF and performed two successful passes along the entire open borehole. After logging was finished, preparations were made to proceed to the next site. The total time spent on Site U1462 was 323.0 h (13.5 d).

A total of 286 cores were recovered from Site U1462. The XCB system (Holes U1462A and U1462B) cored 907.1 m and recovered 322.28 m (36%), while the RCB system

(Hole U1462C) cored 917.0 m and recovered 398.29 m (43%). The overall recovery for Site U1462 was 40%.

Principal Results

Lithostratigraphy

The lithostratigraphy of Site U1462 is divided into four units. Unit I (0–300.9 mbsf (Hole U1462A); 0–47.8 mbsf (Hole U1462B); 33–256.7 mbsf (Hole U1462C)) is characterized by partially to fully lithified, light grayish green to dark greenish gray, non-skeletal packstones with lesser amounts of skeletal pack- to grainstone. The grainstone consists mainly of medium sand-sized to coarse sand-sized grains with minor amounts of gravel and fine sand, and macrofossils, peloids, and ooids. Common macrofossils include bivalves, gastropods, barnacles, solitary corals, echinoderms, scaphopods, bryozoans, brachiopods, and serpulids. Small and larger benthic foraminifera are common, whereas planktic foraminifera are scarce. Some sedimentary structures, such as planar laminations, slight to moderate bioturbation, and sharp to wavy, gradational, and bioturbated contacts are visible in the few cores with greater recovery. The transition from Unit I to Unit II is characterized by the disappearance of large (>250 µm) peloids, a distinct increase in planktic foraminifers and siliciclastic components, and a transition from neritic to hemipelagic facies. Unit II (300.9–777.3 mbsf (Hole U1462A); 256.7–777.88 mbsf (Hole U1462C)) is composed largely of lithified olive gray packstones with some wackestone intervals. Grain size is gradational, from very fine sand-size grains to coarse sand-size grains towards the base of Unit II. Diverse and abundant macrofossils in the upper part of Unit II include bivalves, gastropods, scaphopods, bryozoans, and echinoderms, but bioclasts (mainly bivalve fragments) become much less common with depth. In contrast, small benthic foraminifers are fairly common throughout Unit II. Bioturbation is variable throughout the unit, and there is evidence for gravitational flows and other small-scale mass-transport deposits (e.g., laminations, grading, contact surfaces) towards the base of Unit II. Unit III (777.3–843.03 mbsf (Hole U1462A); 777.88–844.76 mbsf (Hole U1462C)) is distinguished from Unit II by higher quartz content. In Hole U1462A, Unit III consists of lithified, gray to olive gray packstone with fine to medium sand-sized quartz grains and various macrofossils, including bivalves, gastropods, bryozoans, echinoderms, and small benthic foraminifers. In Hole U1462C, the transition between Unit II and Unit III is characterized by a change in the lithology from packstone to grainstone and a marked contact (a pyrite-rich cemented interval). Below the grainstone interval, Unit III is composed mainly of packstone with primarily coarse to medium sand-sized grains; disseminated pyrite is also common. At the base of the unit, the lithology transitions to dark greenish gray, coarse-grained, poorly sorted sandstone, containing common large benthic foraminifers. Bioturbation is more severe in Hole U1462C than Hole U1462A, while sedimentary features (e.g., parallel laminations, grading, bioturbated contacts) are similar throughout the unit in both Holes. Unit IV (843.03–849.6 mbsf (Hole U1462A); 843.48–946.09 mbsf (Hole U1462C)) is composed primarily of dolostone and quartz-rich sandstone and is characterized by common anhydrite nodules, intervals of anhydrite rock, and associated chicken wire structures. The start of Unit IV is defined by the first appearance of macroscopic anhydrite nodules and an increase in dolomite. Unit IV varies in color from light brown to gray to white (anhydrite nodules and anhydrite rock) with generally coarse to medium sand-sized grains, and brief intervals of fine sand. Bioturbation is slight to moderate, but sporadic throughout the unit. Burrows are often filled with dolomite. Macrofossil fragments occur in low numbers throughout the unit, and include solitary corals, bivalves, echinoderms, small benthic foraminifers, and fossil molds (e.g., gastropods and bivalves). Parallel laminations are more frequent in the upper part of the unit, while dissolution cavities and intermittent moldic porosity appear in the lower part. Contact surfaces are uncommon, but if present, typically form sharp, sub-horizontal surfaces. Pyrite grains are intermittently common and sometimes rim intraclasts, quartz, and anhydrite grains.

Biostratigraphy and Micropaleontology

Core catcher (CC) samples from Site U1462 were processed at 20 m resolution. Nannofossil analyses were done at 10 m resolution in selected intervals, to better constrain biostratigraphic datums between Holes U1462A, U1462B and U1462C, and extra benthic foraminiferal samples were taken from selected intervals when specific assemblages were absent from CC samples. The upper 390 m of Site U1462 contain late Pleistocene sediments (<1.93 Ma; NN19–21; Pt1a–b) that yielded very rare nannofossils and planktonic foraminifers. The top occurrence of *Pseudoemiliania lacunosa* at 42.67 mbsf (0.44 Ma), and the top occurrence of *Reticulofenestra asanoi* at 252.5 mbsf (0.91 Ma) are found at similar depths as at Site U1461, whereas older nannofossil (>1.6 Ma) and planktonic foraminifer datums (>1.64 Ma) show an offset between these sites. The Pliocene/Pleistocene boundary is between 527.5 and 539.97 mbsf, based on the (rare) presence of *Discoaster surculus* (2.49 Ma, Top of NN16) and the planktonic foraminifer *Globorotalia limbata* (2.39 Ma, Top of PL5; Gradstein et al., 2012). The microfossil and planktonic foraminifer abundance and preservation improved in the early Pleistocene–Pliocene and the earliest Pliocene–late Miocene intervals between ~325 mbsf (Samples U1462A-35X-CC and U1462C-62R-CC) and 827 mbsf (Samples U1462A-95X-CC and U1462C-153R-CC). Despite the improvement in preservation and abundance of planktonic foraminifers at 368 mbsf, both are still relatively poor compared to Sites U1460 and U1461. The highest diversity is encountered in samples deeper than 420 mbsf (Core 356-U1462A-87X-CC), which contain up to 90% planktonic foraminiferal taxa. As the general preservation is poor, some of the biozone markers found at previous sites, such as *Globorotalia limbata*, *Pulleniatina primalis*, and *Sphaeroidinellopsis seminulina,* are rare and often occur deeper than their expected stratigraphic position. Below ~820 mbsf, planktonic foraminiferal abundance markedly decreases and samples are mostly barren. The bottoms of Holes U1462A (849.67 mbsf) and U1462C (946.09 mbsf) are barren of microfossils, but Samples U1462A-91X-CC to 95X-CC (807.55–827.46 mbsf) and U1462C-149R-CC to 153R-CC (809.15–827.65 m CSF-A) yield a late Miocene age based on the presence of the nannofossils *Discoaster quinqueramus* (defining the NN11/NN12 boundary at 5.59 Ma) and *Reticulofenestra rotaria* (short range within NN11B).

The samples from Holes U1462A to U1462C contain between 9%–100% benthic foraminifera with *Cibicides* spp. and *Cibicidoides* spp. as the most common taxa. Seven assemblages can be identified based on the abundance of *Operculina* spp. and *Discorbinella spp.* (Assemblage 1)*, Amphistegina* spp. and *Elphidium* spp. (Assemblage 2)*, Melonis* spp., *Discorbinella* spp. and *Nonionoides* spp. (Assemblage 3), *Lenticulina* spp., Brizalinids and Bolivinids (Assemblage 4, 6, and 7), *Pseudorotalia* spp.*, Siphogenerina raphana* and *Neoeponides margaritifer* (Assemblage 5), and *Uvigerina* spp. (Assemblage 6). One to 36 species are present in the samples and the assemblages show a deepening palaeodepth downhole from an inner shelf setting (Assemblages 1–3) to a middle to outer shelf setting (Assemblages 3–5) and finally an outer shelf to upper bathyal/deeper setting (Assemblages 6–7). This overall deepening trend is interspersed with transported shallow taxa (Assemblage 7). Preservation varied from very good to poor throughout the site and was affected by fragmentation, abrasion, and encrustation.

Geochemistry

Site U1462 is characterized by low concentrations of headspace gases. Relatively high concentrations of calcium carbonate (up to 89.4%) are noted above 845 mbsf. At approximately 850 mbsf, a major drop in calcium carbonate content to 3.3% occurs, denoting the transition into the quartz-rich siliciclastics of the Bare Formation (Wallace et al., 2003). Low values of TOC (mean value 0.7%) and total nitrogen (mean value 0.017%) characterize the upper 845 m. As at previous Expedition 356 sites U1459, U1460, and U1461, high salinity characterizes interstitial waters with a mean value of 123 and a maximum of 153. Elevated salinity at Site U1462, 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. A zone of sulfate reduction is observed between approximately 300 and 500 mbsf.

Paleomagnetism

Paleomagnetism investigations focused on natural remanent magnetization (NRM) and alternating field demagnetization (AFD) measurements. As core recovery and quality in Holes U1462A and U1462C was poor, only archive-half core sections below 300 mbsf from Hole U1462C were measured using the superconducting rock magnetometer (SRM). However, stepwise AF demagnetization was conducted for 24 discrete samples from Hole U1462A. Additionally, isothermal remanent magnetism (IRM) acquisition and backfield IRM measurements were performed on four discrete samples from Hole U1462A (U1462A-43X-1W, 49–51 cm; U1462A-54X-1W, 38–40 cm; U1462A-85X-2W, 51–53 cm; and U1462A-93X-1W, 38–40 cm). The samples chosen were representative of sediments that yield high and low magnetic susceptibility values from the upper and lower part of the hole. The samples that exhibit low susceptibility (43X-1W, 49–51 cm, and 93X-1W, 38–40 cm) exhibit SIRM patterns that indicate the presence of magnetite and/or titanomagnetite. The other two samples (54X-1W, 38–40 cm, and 85X-2W, 51–53 cm) showed higher SIRM values (~700 mT) and bimodal behavior, indicating higher coercivity and possibly the presence of pyrrhotite. Remanent coercivity values of the four samples ranged between 46 and 58 mT. Sample U1462A-85X-2W, 51–53 cm, was AF demagnetized after acquiring IRM, yielding a median destructive field of 40 mT. Bulk susceptibility measurements were also performed on all 24 discrete samples, and results ranged from -6.88×10^{-6} to 48.05×10^{-6} SI units. Alternating field cleaning procedures were followed by principal component analysis (PCA) for the discrete samples from Hole

U1462A, which indicated two different patterns: 1) low coercivity from the top of the hole down to ~504 mbsf, and 2) higher coercivity from ~580 mbsf to the last measured sample at 836.8 mbsf. This suggests that AF demagnetization on the SRM up to 20 mT for archive-half core sections (Hole U1462C) may not be sufficient to fully reveal the ChRM below ~580 mbsf. Examination of high coercivity component 2 data from the PCA of discrete samples from ~580 mbsf to the bottom of Hole U1462A reveals steeper inclination values than those observed for component 1. These steeper inclination values may not originate from a drilling overprint and can be correlated with the early part of the Matuyama chron (C1r), although the wide spacing between discrete samples means that the interpretation of chron boundaries remains inconclusive. Magnetostratigraphic data for Hole U1462C clearly indicate a prominent bias of inclination data towards positive values between Cores U1462C-104R and 114R (~537.6–586.0 mbsf) that, based on the biostratigraphic datums of 3.54 Ma (565.6 mbsf) and 3.70 Ma (584.7 mbsf), could be related to the upper part (C2Ar) of the Gilbert chron.

Physical Properties

Physical properties measurements at U1462 were carried out using the Whole-Round Multisensor Logger (WRMSL), natural gamma ray (NGR) sensor, and discrete sampling. Due to poor recovery, WRMSL and NGR data are scarce above 300 mbsf. However, below 300 mbsf, 60%–70% core recovery resulted in good coverage by these instruments. Between 300–840 mbsf, magnetic susceptibility (MS) and NGR tend to be in phase and show 20–30 m scale variations, suggesting that they both reflect variations in clay input. Discrete *P*-wave measurements were taken in three different ways: on section halves within the liner, on individual rock pieces, and on cut cubes that were subsequently analyzed for moisture and density (MAD). From the seafloor to 300 mbsf and from 850 to 950 mbsf, which correspond to low recovery intervals where measurements were made on lithified fragments, *P*-wave velocities are scattered and range up to ~5500 m/s. The *P*-wave velocities of many MAD cube samples showed that these rocks tended to have a high degree of anisotropy. *P*-wave velocities correlate well with porosity and follow a power relation with bulk density. Grain densities obtained from MAD measurements correlate with grain densities estimated by X-ray diffraction (XRD). Porosities in the packstones of lithostratigraphic Unit II decrease from about 43% at 300 mbsf to 27% at 840 mbsf; the rocks above this unit show variable porosities and those deeper show variable but lower porosities. Thermal conductivity measured in Hole U1462A increases with depth from about 1.3 to 2.4 W/(m·K) at the bottom of the hole (~850 mbsf).

Downhole Logging

Downhole measurements in Holes U1462A and U1462C consisted of runs with the triple combination, the FMS-sonic, and the VSI (Hole U1462C only) tool strings. Unfortunately, the magnetic susceptibility data obtained during wireline logging were judged not to be of sufficient quality for interpretation. The NGR logs for both holes were in agreement. In the upper 300 m, the wireline NGR log is the only available source of information on this sediment property, as core recovery was low (average 4%). Below 300 m WMSF, the NGR log showed good agreement with NGR data obtained on whole-round cores, with values ranging between 15 and 60 cps. Many NGR peaks and troughs observed in cores were also found in the downhole log and were used for core-log correlation. This correlation indicated that the offset between wireline (m WMSF) and coring depth (mbsf) varied between 1 and 4 m. Wireline density and porosity measurements were generally in good agreement with those measured on cores, except for some intervals with irregularities in the borehole diameter (>16.7 inch). Porosity decreased from ~50% at 250 m WMSF to ~30% at 770 m WMSF, whereas bulk density increased from 2.0 to 2.25 g/cm^3 in the same interval. Where the logging underestimated bulk density, it overestimated porosity in comparison to data obtained from discrete samples. The quality of FMS images was generally poor. However, around 625 m WMSF, there are horizontal lineations that were coherent between the four sensing pads, and the character between the two holes was similar. The spacing between these alterations ranged from several tens of centimeters to several meters, with thin (several tens of cm) resistive layers embedded within broader, more conductive areas (1–2 m). Seismic properties were measured both with the FMS-sonic tool string and the vertical seismic profile (VSP) conducted with the VSI. These two methods yielded sonic velocities that were in agreement with one another, which means that the VSP experiment validated the absolute values of the velocities obtained with the FMS-sonic.

Stratigraphic Correlation

A resistant lithology to piston coring in the upper ~300 m at Site U1462 required the use of the XCB (Hole U1462A) and RCB (Hole U1462C) systems from the seafloor. Intervals of high recovery varied with the coring system used, but in general were poorest in the upper 300 m. Recovery in Hole U1463A was relatively high from ~545–585 mbsf (Cores U1462A-58X to 62X), ~635–735 mbsf (69X to 86X) and ~820–845 mbsf (94X to 98X), whereas the highest recovery intervals in Hole U1462C were ~320–370 mbsf (Cores U1462C-62R to 71R), ~460 to 775 mbsf (Cores 91R to 143R) and ~815 to 825 mbsf (Cores 151R to 153R). Unfortunately, within these higher recovery intervals, the cores do not overlap for more than a few meters at a time so a detailed correlation cannot be constructed. However, the wireline gamma ray logs, which correlate well to core-based NGR data, provide an excellent framework for developing windows of high-resolution analyses in higher recovery intervals. For example, Cores U1462A-36X to 40X overlap with Cores U1462C-62R to 65R and 67R to 71R (~325–380 mbsf), Cores U1462A-57X to 61X overlaps with Cores U1462C-101R to 109R (~525–565 mbsf), and Cores U1462A-94X to 98X overlap with Cores U1462C-148R to 157R (~800–840 mbsf).

References

Gallagher, S. J., Wallace, M. W., Li, C. L., Kinna, B., Bye, J. T., Akimoto, K., and Torii, M., 2009, Neogene history of the West Pacific Warm Pool, Kuroshio and Leeuwin currents: *Paleoceanography,* v. 24., doi:10.1029/2008PA001660

Gallagher, S.J., Wallace, M.W., Hoiles, P.W. & Southwood, J. M., 2014, Seismic and stratigraphic evidence for reef expansion and onset of aridity on the Northwest Shelf of Australia during the Pleistocene. *Marine and Petroleum Geology* v. 57, 470–481. doi:10.1016/j.marpetgeo.2014.06.011

James, N. P., Bone, Y., Kyser, T. K., Dix, G. R., and Collins, L. B., 2004, The importance of changing oceanography in controlling late Quaternary carbonate sedimentation on a high-energy, tropical, oceanic ramp; north-western Australia: *Sedimentology,* v. 51, no. 6, p. 1179–1205.

Jones, H. A., 1973, *Marine geology of the Northwest Australian continental shelf:* Bureau of Mineral Resources of Australia, v. 136, p. 58.

Wallace, M.W., Condilis, E., Powell, A., Redfearn, J., Auld, K., Wiltshire, M., Holdgate, G.R., and Gallagher, S.J., 2003. Northwest Shelf - New ideas, new discoveries - Geological controls on sonic velocity in the Cenozoic carbonates of the Northern Carnarvon Basin, Northwest Shelf, Western Australia, *The APEA Journal,* 43, 385–400.