IODP Expedition 356: Indonesian Throughflow
Site U1461 Summary

Background and Objectives

Site U1461 (proposed Site NWS-4A) is 100 km northwest of Barrow Island in the northern Carnarvon Basin near the West Tryal Rocks-2 industry well. It is on the shelf edge of a carbonate ramp (James et al. 2004). The seabed in the region is poorly sorted, carbonate-rich (>90%) sediment made up of bioclastic gravel, sand, and mud (Jones, 1973; James et al., 2004). Coring at Site U1461 targeted a 1 km thick outer-shelf to upper-slope carbonate wedge that onlaps (due to basin-wide subsidence) a regional top Miocene surface.

The primary objective of Site U1461 was to obtain a >4 m.y. orbital-scale record of climate variability and monsoonal history comparable in resolution to other global climate proxy records. Most such records are from the deep ocean basins. However, one benefit of coring this shelf-margin setting is that terrigenous clay and terrestrial palynomorphs should be abundant, delivered by fluvial outflow during the rainy season (van der Kaars & De Deckker, 2003). This location is also close to the Australian monsoonal southern influence and can be used chart its latitudinal variability. Marine microfossil palaeoproductivity analyses at this site should also reveal the dominance of the Western Australian Current over the Leeuwin Current during glacial periods, when the Australian monsoon is thought to have been weak (Gallagher et al., 2014). There are intervals in this section that consist of plankton ooze (Gallagher et al., 2009) deposited at upper to middle slope paleodepths. Therefore, combining C/O and Mg/Ca analyses of microfossils from Site U1461 should produce a Plio–Pleistocene obliquity- (or even precession-) scale record that can be directly compared and correlated to the LR2004 stack (Lisiecki and Raymo, 2005) for chronostratigraphic and paleoceanographic analyses. Site U1461 is down dip from a drowned reef on a paleoshelf edge (Gallagher et al., 2014). By dating the reflectors and correlating these up dip, it will be possible to constrain the age of onset of this reef and other reefs at this level regionally. Furthermore, downslope transported reefal or shelf detritus into this section will enable analysis of reef and ramp development in response to variable sea level.

Operations

Site U1461 consisted of four holes; the objectives were to recover a complete stratigraphy of the upper sedimentary section and to recover material below 1000 mbsf. The first hole (U1461A) was cored to HLAPC refusal (284.7 mbsf). There was a single hard layer encountered at ~54 mbsf, so an XCB core barrel was dropped and 2.5 m was cored with that system. Based on the results from Hole U1461A, a coring plan for Hole U1461B utilizing both piston coring and XCB coring was prepared to minimize recovery gaps. All APC cores were oriented. Hole U1461B was successfully piston cored to 375.2 mbsf. The XCB coring system was then deployed and coring continued with good recovery to a final depth of 879.2 mbsf. Coring was terminated after the XCB cutting time for each core exceeded ~90 min. The third hole (U1461C) was used to fill in remaining recovery gaps in the upper sedimentary section to aid stratigraphic correlation and to try to deepen piston coring to recover gaps in recovery from the XCB system used in Hole U1461B. The hole was successfully piston-cored to 443.9 mbsf with one 3 m interval drilled without coring to aid correlation. There were four in situ temperature measurements taken and all APC cores (U1461C-2H to 23H) were oriented. Hole U1461D was cored with the RCB system to achieve the deep objective of the site. Hole U1461D was first drilled without coring to 455.0 mbsf with a center bit installed. The center bit was pulled and RCB cores were recovered from 455.0–474.4 mbsf. The center bit was deployed again and the hole deepened by drilling without coring to 503.0 mbsf. At that depth, a single 9.7 m core was cut and then drilling continued to 565.0 mbsf. Continuous RCB coring then extended from 565.0 mbsf to a final depth of 1095.3 mbsf. After the completion of coring, the hole was conditioned for logging and the upper ~500 m was displaced with heavy mud. Two separate logging tool strings were deployed. The triple combination tool string reached ~1030 mbsf. While logging up from depth, there were indications of a hole collapse. The FMS-sonic tool string was deployed, but only reached a total depth of ~190 mbsf before encountering a bridge. After several attempts to pass the bridge, logging was terminated and preparations were made to proceed to the next site.

A total of 301 cores were collected at Site U1461. The APC coring system was deployed 70 times, the HLAPC system was deployed 100 times, the XCB coring system was deployed 73 times, and the RCB coring system was deployed 58 times. The APC system cored 636.9 m and recovered 654.18 m of core (103%). The HLAPC system cored

455.0 m and recovered 464.99 m of core (102%). The XCB system cored 512.9 m and recovered 360.19 m of core (70%). The RCB system cored 559.4 m and recovered 325.51 m of core (58%). The overall percentage recovery for Site U1461 was 83%. The total time spent on Site U1461 was 294.75 h (12.3 d).

Principal Results

Lithostratigraphy

The lithostratigraphy of Site U1461 is divided into four units, with six subunits in Unit II. The lithostratigraphic units and their boundaries are defined by changes in lithology (identified by visual core description and smear slide observations), physical properties, color reflectance (L*, a* and b*), XRD, petrographic section analyses, and seismic data. Unit I (0–11.00 mbsf (Hole U1461A), 0–11.30 mbsf (Hole U1461B), 0–11.40 mbsf (Hole U1461C)) consists of mainly unlithified, homogeneous olive gray to brown to greenish gray packstone with benthic foraminifers and bivalves. Unit II (11.00–284.71 mbsf (Hole U1461A), 11.30–466.40 mbsf (Hole U1461B), 11.40–443.88 mbsf (Hole U1461C), and 455.00–466.98 mbsf (Hole U1461D)) is divided into six subunits (IIa, IIb, IIc, IId, IIe, IIf in descending order). In Unit II, all subunits except Subunit IIa consist of two intervals: 1) an upper coarser-grained, darker-colored, thicker interval composed of unlithified, dark greenish gray to olive gray packstone/wackestone, and 2) a lower, finer-grained, light-colored, thinner interval composed of unlithified, homogeneous, cream to light gray mudstone. The exception, Subunit IIa, consists entirely of a light-colored mudstone/wackestone. Throughout Unit II, the lower interval of each subunit is always thinner than the upper interval. These upper and lower intervals are further distinguished by differences in degree of bioturbation, and abundance of macrofossils, peloids, and, in the case of Subunit IIf, the presence of low-angle cross stratification and normal grading. Unit III (466.40–877.64 mbsf (Hole U1461B) and 466.98–992.88 mbsf (Hole U1461D)) is composed of lithified wackestone ranging in color from greenish gray to olive gray. Bioturbation is common throughout the unit, and burrows are often filled with coarse sand. Foraminifers are common, whereas fragments of bivalves and gastropods are rare. In the lower half of Unit III there are a variety of sedimentary contacts, ranging from sharp to wavy, gradational, and scoured. The occurrence of these contacts often coincides with numerous sedimentary features, including parallel lamination, thin bedding, normal grading, load casts, slump folds, and intraclasts. Pyrite is also present in the lower half of Unit III as disseminated grains and

nodules. Unit IV (992.88–1088.92 mbsf (Hole U1461D)) consists of lithified, light greenish gray, fine sand-sized packstone (interbedded with wackestone with mud-sized grains) that grades into creamy gray packstone with coarse sand-sized grains (interbedded with packstone with coarser sand-sized grains). Near the base of the unit, the lithology transitions to back to light greenish gray packstone with fine sand-sized grains, interbedded with wackestone with mud-sized grains. Bioturbation, benthic foraminfers, and pyrite are more abundant in muddy intervals. Bedding contacts are sharp. Planar laminae and normal grading are present in the coarser-grained intervals.

Biostratigraphy and Micropaleontology

Core catcher (CC) samples from Site U1461 were analyzed at 20 m resolution through Holes U1461A, U1461B, and U1461D. At Hole U1461C, sampling focused on the top 53 mbsf (Cores U1461C-1H to 6H; 0–53.48 mbsf) and below ~370 mbsf (Samples U1461C-57F-CC to 73F-CC, 443.88 mbsf). The bottom of Holes U1461A (287.7 mbsf) and U1461C (443.88 mbsf) are of early Pleistocene age (base of NN19, <1.93 Ma). The sediments retrieved from Hole U1461B (a total of 129 cores) are of Pliocene–Pleistocene age, with the bottom (879.2 mbsf) estimated to be older than 4.07 Ma (based on planktonic foraminifers). Hole U1461D was analyzed from 456.36 to 1088.9 mbsf. The abundance and preservation of calcareous nannofossils and planktonic foraminifera significantly decreased from Sample U1461D-52R-CC (1008.3 mbsf) downhole, with possible reworking, suggesting a probable unconformity. The bottom of Hole U1461D was dated to the middle to late Miocene (<12.38 Ma–8.79 Ma; nannofossils).

Samples from Holes U1641A to U1641D contain between 5%–91% benthic foraminifera with *Cibicides* spp. and *Cibicidoides* spp. as the most common taxa. Six assemblage trends can be identified by the abundances of *Amphistegina lessonii*, *Hyalinea baltica*, *Sahulia barkeri* (Trend 1), *Elphidium* spp. (Trend 2), *Neoeponides margaritifer* (Trend 3), *Uvigerina* spp. (Trend 4), *Nodosaria* spp. and *Stilostomella* spp. (Trend 5), and *Globocassidulina subglobosa* (Trend 6). Seven to 63 species are present in the samples. Preservation varied from medium to poor throughout the site and was affected by fragmentation and abrasion.

Geochemistry

At Site U1461, 140 samples were analyzed for headspace gas content, 38 samples (5–15 cm whole rounds) for interstitial water geochemistry measurements, and 38 samples

for total organic carbon, carbonate, and total nitrogen. No interstitial water samples were collected in Holes U1461C and U1461D. Hole U1461C recovered a section previously sampled in Holes U1461A and U1461B, and the lithology at the bottom of Hole U1461B (879.2 mbsf) yielded insufficient pore water, so there was no possibility of obtaining sufficient amounts of pore water from deeper intervals in Hole U1461D. In general, elevated salinity characterizes the site, with a value of 35 at the top, increasing gradually with depth to a value of 137 at 870 mbsf. Coincident increasing trends of bromide, chloride, and sodium in the interstitial water samples with depth are consistent with the salinity record. Increasing trends of alkalinity, pH, and ammonium, and a decreasing trend of sulfate, indicate a reduction zone in the upper 100 m of the site. Finally, the site is characterized by high percentages of calcium carbonate (mean value of ~80%) and low total organic carbon (mean value of 0.9%) and total nitrogen (mean value of 0.04%).

Paleomagnetism

Paleomagnetic investigations focused on natural remanent magnetization and partial alternating field demagnetization (AFD) measurements from Site U1461. To address some technical issues (flux jumps) related to the superconducting rock magnetometer (SRM) measurements from Holes U1461B and U1461C, a representative group of discrete samples underwent AF demagnetization and were compared to the SRM directional datasets to provide reliable magnetostratigraphic interpretations. This issue was properly fixed for Hole 1461D archive-half section measurements. For Holes U1461B and U1461C, comparisons between results from the archive-half and discrete sample measurements indicate normal (negative) overprint until 30–50 mT demagnetization steps, which were not fully removed after SRM AF demagnetization procedures (up to 20 mT). Isothermal remanent magnetization (IRM) and backfield IRM acquisition curves were also produced to investigate rock magnetism properties. Most samples seem to reach the IRM between 100 and 300 mT, indicative for a wide range of magnetic carriers, and this was verified for a narrow range of coercivity of remanence values (45–50 mT). Complementary X-ray diffraction measurements of one sample from Hole U1461B indicated the presence of low (e.g., magnetite, titanomagnetite, maghemite), intermediate (e.g., greigite), and high (e.g., hematite, greigite, and goethite) coercivity phases. Magnetostratigraphy for Hole U1461C indicated the Brunhes/Matuyama boundary (0.781 Ma) is between 45–65 mbsf, and the Jaramillo subchron (0.988 Ma) is between 281–316 mbsf. Hole U1461D magnetostratigraphic data

indicated a succession of magnetozones in good agreement with biostratigraphic datums, which pointed to the Matuyama/Gauss (2.581 Ma) and Gauss/Gilbert (3.596 Ma) boundaries at 725 mbsf and ~827 mbsf, respectively, as well as the C3n.4n (Thvera) interval (4.997–5.235 Ma), close to the Pliocene/Miocene boundary.

Physical Properties

Physical properties measurements at Site U1461 were performed using the Whole-Round Multisensor Logger (WRMSL), natural gamma ray (NGR) sensor, and discrete sampling. Light colored sediments were discriminated by high L* values and corresponded to relatively low magnetic susceptibility (MS) and high grain density (GRA). This pattern was interpreted to result from high micrite and a low detrital clay component in these sediments. In cores that were obtained by the XCB and RCB systems, GRA tended to underestimate bulk density because core liners were not fully filled due to the variation in core diameter. The same pattern was observed when MS measurements on the WRMSL and the Section Half Multisensor Logger (SHMSL) were compared. Thermal conductivity of sediments increased gradually with depth, from about 1 W/(m·K) in the upper portion of Holes U1461A and U1461B, to ~1.8 W/(m·K) at ~1000 mbsf in Hole U1461D. These measurements were used in combination with downhole in situ temperature measurements to calculate a geothermal heat flux of 41.1 mW/m^2. Between 125–450 mbsf, sonic velocity measurements by both WRMSL and discrete sampling were often unsuccessful, as the cored material was characterized by a large degree of expansion, hampering such measurements. However, in the deeper parts of Holes U1461B and U1461D, discrete measurements of sonic velocity were successful and show a gradual increase with depth from ~1750 m/s (450 mbsf) to ~2800 m/s (925 mbsf). In the lower part of Hole U1461D (925–1080 mbsf), sonic velocities were relatively constant and ranged between 2400 and 2900 m/s. Porosity was about 60% to 70% in the top 50 m and decreased to 28%–34% at the bottom of the deepest hole (Hole U1461D). Grain densities tended to average about 2.75 g/cm^3, with high values reflecting the presence of aragonite, which occurred in varying amounts in the top half of the cored interval (upper ~600 m).

Downhole Logging

Downhole measurements in Hole U1461D consisted of runs with the triple combination and the Formation MicroScanner and sonic tool strings (FMS-sonic). Unfortunately, the

magnetic susceptibility and FMS data obtained during wireline logging were judged not to be of sufficient quality for interpretation. The NGR log data showed good agreement with data obtained on whole-round cores. In the upper 450 m, the NGR was relatively low, except for some distinct peaks. At 450 m wireline below seafloor (WSF) there was a stepwise increase of NGR towards values of about 35 cps; in the interval between 450–820 m WSF, NGR fluctuated around 35 cps, increased further to 40 cps between 820–850 m WSF, and then was stable between 850–1000 m WSF. Many NGR peaks and troughs observed in cores were also found in the downhole log and were used for core-log correlation. The NGR data showed that the large peaks in the upper 460 m were mainly driven by variations in U content. This correlation indicated that the offset between wireline (m WSF) and coring depth (mbsf) varied between 4 and 8 m throughout Hole U1461D. In the upper 450 m WSF, density and porosity measurements were unreliable due to partial collapse of the hole, but >450 m WSF there was good agreement between the values logged and those measured on cores. Porosity decreased from ~48% at 450 m WSF to ~30% at 1030 m WSF, whereas bulk density increased from 2.0 to 2.2 g/cm^3 in the same depth interval. Overall, where the logging underestimated bulk density, it overestimated porosity in comparison to data obtained from discrete samples.

Stratigraphic Correlation

The upper 285 m of Site 1461 was tripled cored using a combination of the piston coring (APC, HLAPC) and XCB systems. This interval was correlated and a splice was generated, although there is less confidence in the correlation in some intervals between 240 and 285 mbsf. This is related to the low variation in natural gamma ray and magnetic susceptibility data (e.g., Cores U1461A-30F to 31F, U1461B-27F to 29F, and U1461C-26F to 28F) coupled with the recovery of 4.7 m cores (HLAPC) instead of full length (9.5 m) APC cores. While the HLAPC enabled greater recovery of high quality core overall, the relative size of the gaps between cores is greater than with APC and a high affine growth factor (a measure of the fractional stretching of the composite section relative to the drilled interval which was ~114%) also made correlation more challenging. The deeper section penetrated in Holes U1461B (Cores 81X to 126X) and U1461D (Cores 5R to 61R) was also correlated, but significant recovery gaps do not permit the development of a continuous section.

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