IODP Expedition 363: Western Pacific Warm Pool

Site U1482 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1482 (proposed Site WP-12D) is located on the northwest Australian margin at 15°3.32′S, 120°26.10′E and 1466 m below sea level (mbsl). The site is situated at shotpoint 440 on seismic Line HBR2000A-3032, ~581 m northwest of the cross-point of seismic Lines HBR2000A-3032 and BR98-84. The top of the first prominent reflector, originally interpreted as the middle Miocene sequence boundary (Mi-3; 13.8 Ma), is 0.55 s two-way traveltime (TWT) below the seafloor, equivalent to ~500 m below seafloor (mbsf). Site U1482 is on the Scott Plateau, which corresponds to a subsided platform area that forms the northwestern flank of the northeast-trending Browse Basin (Keep et al., 2007). This region, which is adjacent to some of the oldest ocean crust still in the world's ocean (Argo Abyssal Plain), has remained a stable passive margin since the breakup of Gondwanaland and the separation of northwest Australia from the Tethyan landmass (Gradstein et al., 1992). As a result of the northward movement of the Australian plate, continuous Neogene deformation along the normal faults that bound the Scott Plateau led to the amplification of relief between the Browse Basin and Scott Plateau and may have resulted in some of the downslope sediment transport seen in the seismic profiles (Keep et al., 2007) and sediment deformation in the cores recovered at this site.

The Mesozoic section beneath the Scott Plateau is strongly influenced by breakup-related tectonics, which forms the acoustic basement through much of the Scott Plateau area (Stagg and Exon, 1981). The post-breakup sedimentary succession forms a ~2000 m thick, relatively uniform blanket over the Scott Plateau and the northeastern margin of Browse Basin. The extended Miocene to recent sedimentary succession recovered at Site U1482 provides an ideal archive to reconstruct the climate and circulation history at the southwestern edge of the Indo-Pacific Warm Pool (IPWP) at higher resolution than available at the nearby deep sea Ocean Drilling Program (ODP) sites (e.g., Site 761 on the Wombat Plateau; Holbourn et al., 2004).

The location of Site U1482 is within the prominent hydrographic front separating tropical and subtropical water masses, which makes it suitable to monitor changes in the southward extent of tropical warm water related either to circulation or global climate trends. The site is situated close to the oceanographic front between relatively cool, nutrient-rich water carried northward in the Eastern Indian Ocean by the West Australian Current and warm, oligotrophic Leeuwin Current waters, which results in a steep north–south sea-surface temperature (SST) gradient. This strategic location will allow reconstruction of the southwestern extent of the IPWP and monitoring of the Indonesian Throughflow (ITF) outflow into the Indian Ocean since the early late Miocene.

The extended sediment archive recovered at Site U1482 will enable reconstruction of climate variability on orbital timescales over the past ~10 my, which will complement high-resolution records from the Pacific, Atlantic, and Southern Oceans, and will be crucial for constraining regional and global circulation modes and Miocene ice volume variations. The new Pliocene record from Site U1482 is also ideally suited to test the hypothesis of a major restriction of warm water throughflow originating from the South Pacific Ocean between 3 and 5 Ma due to the northward movement of Papua New Guinea, which may have been a key factor in the aridification of East Africa and hominid evolution (Cane and Molnar, 2001).

Operations

After a 1514 nmi transit from Singapore, the vessel stabilized over Site U1482 at 1524 h (UTC + 8 h) on 16 October 2016. We cored four holes at Site U1482 (WP-12D). The original operations plan called for three holes: the first to advanced piston corer (APC) refusal, followed by two APC holes with extended core barrel (XCB) coring down to 490 mbsf (our approved depth of penetration for the site). The plan was modified to core to total depth (490 mbsf) in the first hole to determine the operations plan for the remaining holes.

We reached APC refusal at ~345 m below seafloor (mbsf) in Hole U1482A. We opted to deepen the hole with the half-length advanced piston corer (HLAPC), which reached to 380 mbsf before hitting refusal. We then switched to the XCB to core to the total approved depth of 490 mbsf. Hole U1482B was cored to 343.6 mbsf with the APC and then to 366.6 mbsf using the HLAPC. This hole included five intervals drilled without coring to avoid core gap alignment for stratigraphic correlation. Since the age of the sediment at the bottom of Hole U1482A was several million years younger than anticipated, we requested and received permission to core deeper. Hole U1482C was cored to 335.4 mbsf with the APC and then to 534.1 mbsf with the XCB. We opted to terminate drilling at that depth due to deteriorating calcareous microfossil preservation below 500 mbsf and the increasing length of time to cut cores.

After conditioning the hole for logging, we conducted two downhole logging runs using the triple combo and Formation MicroScanner (FMS)-sonic logging strings in Hole U1482C. The triple combo logging string reached the bottom of the hole at 534.1 mbsf. The FMS-sonic logging string encountered some fill and reached only to 510.5 mbsf. Two upward passes were conducted with the FMS-sonic logging string. Following logging, we opted to core Hole U1482D to target three core gaps in the stratigraphic section. We took one core at the seafloor to establish the seafloor depth before drilling ahead to 137.0 mbsf. We then took eight APC cores to 213.0 mbsf, successfully covering the targeted core gaps. We then terminated the hole, ending operations at Site U1482 at 1800 h on 25 October. Total time spent on Site U1482 was 218.5 h (9.1 d).

A total of 163 cores were collected at this site. The APC coring system was deployed 115 times, collecting 1128.0 m of sediment over 1077.3 m of penetration (105% recovery). The HLAPC coring system was deployed 13 times, recovering 57.01 m of sediment over 55.3 m of penetration (103% recovery). The XCB coring system was deployed 35 times, collecting 305.32 m of sediment over 304 m of penetration (100% recovery).

Principal Results

The sediment cored at Site U1482 is assigned to a single lithologic unit composed of ~535 m of upper Miocene to Pleistocene nannofossil ooze/chalk with varying amounts of clay and foraminifers. Lithologic Unit I is divided into four subunits. Lithologic Subunit IA is a ~120 m thick sequence of Pleistocene light greenish gray clay-rich nannofossil ooze. This subunit contains pteropods and is largely homogenous with variable amounts of clay. In the lower 40 m darker/lighter bedding cycles become more evident. The boundary between Subunits IA and IB marks a sharp transition between darker clay-rich foraminifer-rich nannofossil ooze and dominantly lighter nannofossil ooze. Subunit IB (lower Pliocene to lowermost Pleistocene) is an ~90 m thick greenish gray nannofossil ooze, with clay content increasing towards the middle of the subunit and then decreasing again towards the base. The middle part of Subunit IB also contains an interval of significant soft sediment deformation at a depth of ~150 mbsf. Sulfide specks and nodules are abundant and foraminifer content increases towards the bottom of the subunit. The base of Subunit IB is the first downhole occurrence of well-defined light-dark cycles. Subunit IC (~160 m thick) consists of upper Miocene to lowermost Pliocene light greenish gray nannofossil ooze with varying abundances of foraminifers and clay. This subunit shows strong color cyclicity at a section scale, with cycles largely reflecting changes in carbonate content (~80 to 50 wt%). Sulfide patches are abundant throughout. The base of the subunit is defined by the transition from ooze to chalk, which corresponds to the switch from the HLAPC to XCB coring system in Hole U1482A. Subunit ID is composed of upper Miocene light greenish gray chalk with low abundances of clay. Color cycles are on the order of 1.5 to 2 m thick in this subunit. Dissolution of foraminifers has resulted in moldic porosity within the chalk. Foraminifers are also occasionally concentrated in discrete layers in Subunit ID.

Calcareous nannofossils and planktonic foraminifers are abundant and benthic foraminifers are present throughout the recovered succession at Site U1482 and generally show very good to excellent preservation. Planktonic to benthic ratios are typically 99:1. The age model for Site U1482 is based on calcareous nannofossil and planktonic foraminifer biostratigraphy. The base of the upper Pleistocene is placed at ~3 mbsf, between biohorizon top *Globigerinoides ruber* (pink) (0.12 Ma) and biohorizon base *Emiliania huxleyi* (0.29 Ma). The base of the middle Pleistocene is placed between 47 and 80 mbsf, between the top of *Globorotalia tosaensis* (0.61 Ma) and the top of *Helicosphaera sellii* (1.26 Ma). There is strong evidence for sedimentary disturbance and reworking in the lower and middle Pleistocene with the potential for missing a section in the upper part of the lower Pleistocene. The Pliocene/Pleistocene boundary is placed at 118 mbsf. There are concentrations of planktonic foraminifer biohorizons at ~102–103 mbsf (~1.3 to 1.9 Ma) and 300 mbsf (~6.1 to 6.6 Ma), suggesting condensed intervals or hiatuses. This is less clear in the calcareous nannofossil biohorizons, although nannofossil age control is sparse at both these levels. Otherwise, sedimentation appears continuous throughout the upper Miocene and lower Pliocene interval. The age at the base of the recovered stratigraphy is best constrained as less than 10.47 Ma by the absence of the planktonic foraminifer *Paragloborotalia mayeri* in the lowermost sample examined, although calcareous nannofossil assemblages suggest a slightly older age of ~10.75 Ma. Calcareous nannofossil and planktonic foraminifer biohorizons are in generally good agreement, and indicate sedimentation rates of ~5.9 cm/ky in the upper Miocene, decreasing to ~3.3 cm/ky in the lower Pliocene. The Pleistocene is characterized by higher sediment rates of ~7 cm/ky.

Paleomagnetic investigations at Site U1482 measured natural remanent magnetization (NRM) of archive halves from Holes U1482A, U1482B, and U1482C, before and after demagnetization in a peak alternating field (AF) of 15 mT, which effectively removed the vertical overprint induced by the drill string. Fifty discrete samples were taken to investigate paleomagnetic carriers and rock magnetic properties. NRM_{15mT} intensity is higher (~10^{-4} Am^{-1}) in the upper 40–60 mbsf of each hole, decreases between 60 and 90 mbsf, and remains low (~10^{-5} Am^{-1}) below ~90 mbsf where it approaches the measurement noise level of the magnetometer. Decreases in magnetic intensity downcore are accompanied by decreases in other ferrimagnetic concentration parameters (anhysteretic remanent magnetization [ARM] and isothermal remanent magnetization [IRM]), a halving of the NRM_{15mT}/NRM intensity, and a coarsening of magnetic grain size (lower ARM/saturation remanent magnetization [SIRM]). These changes are coeval with decreases in interstitial water sulfate and the appearance of pyrite in the sediment associated with the reduction of primary ferrimagnetic oxides and formation of secondary iron sulfides during early sediment diagenesis. In the upper 50–70 mbsf, inclinations plot around those expected for the site latitude assuming a geocentric axial dipole (GAD) field. Azimuthally corrected declination using the Icefield MI5 tool is largely consistent between successive cores, but maintains an absolute offset of 150°–180° (i.e., corrected values for normal polarity cluster between 150° and 180° instead of 0°). Relatively weak magnetic susceptibility coupled with reduction of ferrimagnetic oxides results in a largely uninterpretable signal below the iron reduction zone and restricts our geomagnetic interpretation to the upper 50–70 mbsf. Sediment in this zone appears to have been deposited during a period of normal polarity consistent with the Brunhes Chron (C1n).

The physical property data collected for Site U1482 includes *P*-wave velocity, gamma ray attenuation (GRA) bulk density, magnetic susceptibility (MS), natural gamma radiation (NGR), and thermal conductivity on whole-round cores from Holes U1482A to U1482D and additional measurements on split cores and discrete samples including *P*-wave velocity, porosity, and bulk, dry, and grain densities. Thermal conductivity was also measured on split cores when the sediment became too indurated to use the needle probe. Despite the relatively homogeneous lithology dominated by nannofossil ooze at this site, physical property parameters display broad scale features and high-resolution cyclicity throughout the sequence. A downhole, linear increase is superimposed on these high frequency cycles in thermal conductivity (~1.0 to 1.5 W/m·K]), gamma ray attenuation (GRA) bulk density (~1.4 to 2.0 g/cm^3), and moisture and density (MAD) dry density (0.8 to 1.5 g/cm^3) and wet bulk density (1.4 to 2.0 g/cm^3), whereas porosity decreases with depth from ~75% to 45%, representing increasing compaction with depth. Notably, GRA bulk density, NGR, and MS exhibit a broad peak centered at ~175 mbsf, which coincides with an interval of soft sediment deformation observed in all holes. Formation temperature measurements made with the APCT-3 on Cores U1482A-4H, 7H, 10H, and 13H indicate a geothermal gradient of 48°C/km for the upper ~120 mbsf.

Correlations among holes at Site U1482 were accomplished using Correlator software (version 2.1). Tie points were established mainly with Whole-Round Multisensor Logger (WRMSL) MS data, although some were based on WRMSL GRA bulk density and NGR data. Correlation was challenging due to intervals with very low amplitude variability in the WRMSL and NGR signals, the presence of intervals containing soft sediment deformation, and variations in the size of core gaps resulting from a large tidal range of 3–4 m during coring operations at Site U1482. The core composite depth below seafloor (CCSF) depth scale is anchored to the mudline Core U1482B-1H, which is assigned the depth of 0.0 m CCSF. From this anchor, we worked downhole, using Correlator, to establish a composite stratigraphy on a core-by-core basis. We developed a splice from 0–451.2 m CCSF and a composite depth scale to 614.6 m CCSF. The match between the holes is well constrained within the splice, except for intervals of soft sediment deformation (0–17 m CCSF, 55–84 m CCSF, 104–111 m CCSF, and 207–210 m CCSF) and one core gap at 401 m CCSF. Below 451 m CCSF, we determined tentative correlations between some cores, but did not construct a splice, which should be explored as part of postcruise research.

The inorganic geochemistry of Site U1482 is strongly influenced by the remineralization of organic matter. Total organic carbon (TOC) content is >1.0 wt% in the top ~100 mbsf, which is relatively high for an open marine setting. The sediments rapidly become suboxic, as evidenced by a Mn^{2+} peak in the interstitial water profile at ~20 mbsf. Sulfate reduction occurs until ~120 mbsf, where near-complete sulfate depletion is accompanied by a rapid increase in methane. This sulfate/methane transition zone (SMTZ) is also marked by a pronounced increase in [Ba^{2+}] in the interstitial waters, reflecting both authigenic precipitation and dissolution of sedimentary barite ($BaSO_4$) in underlying sediments. Peak alkalinity and [Si] values observed between 0 and 120 mbsf indicate organic matter and biogenic silica remineralization, respectively. The steady increases in [NH_4^+] and [Br^-] are also consistent with this progressive remineralization of organic matter. Calcium and magnesium concentrations decrease in the upper 120 mbsf, possibly reflecting calcite precipitation. A similar trend of decreasing phosphate suggests possible precipitation of apatite, although overall [PO_4^{3-}] is quite low (<10 μmol). Below 120 mbsf, [Mg^{2+}] continues to decrease, whereas [Ca^{2+}] shows a slight increase. Although this suggests precipitation of dolomite, downhole trends in [K^+], [B], and [Li^+] indicate that ion exchange with clay minerals could contribute to the trends observed in the interstitial water profiles.

Hydrocarbon monitoring shows elevated methane concentration below the SMTZ, with an average of 6%. However, the ratio of methane to ethane, as well as the gas wetness index, suggest that most of the gas has a biogenic origin. The methane concentration decreases to ~3% between ~380 and 530 mbsf, reflecting progressive depletion of available organic matter for methanogenesis. Both ethane and propane profiles largely follow methane, but also respond to the increased thermal maturity following the geothermal gradient.

The carbonate content at Site U1482 fluctuates between 0 and 180 mbsf, with an average of ~60 wt%. Below 180 mbsf, $CaCO_3$ content increases to about 80 wt%, possibly reflecting the late Miocene to early Pliocene "biogenic bloom" that is most pronounced in the Indo-Pacific region (e.g., Farrell et al., 1995; Gupta and Thomas, 1999).

Two downhole logging tool strings were run in Hole U1482C, the triple combo (NGR, porosity, density, electrical resistivity, and magnetic susceptibility) and the FMS-sonic (NGR, sonic velocity, and electrical resistivity images). The triple combo reached to the bottom of the hole at 534.1 mbsf, whereas the FMS-sonic reached only to 510.5 mbsf after encountering fill. One of the four FMS pads performed poorly; however, postacquisition processing corrected the problem. The increase in gamma radiation at the seafloor matched well with the driller's depth. Caliper data show that the borehole was enlarged by ~2.5 to 10 cm in the upper 250 mbsf, which affected the quality of the density and porosity measurements and resulted in higher variability in those data. Below 350 mbsf, corresponding to the depth where we switched to XCB coring, the borehole walls were remarkably smooth. This interval corresponds to lithologic Subunit ID, which consists of chalk.

The composite gamma ray log shows an increase between 115 and 205 mbsf (lithologic Subunit IB), which correlates with an increase in NGR measured on cores, indicating a higher proportion of clay over that interval. Shallow and deep resistivity measurements show consistent offset downhole, indicating that there was little or no fluid invasion into the formation. *P*-wave velocities increase steadily downhole to roughly 2000 m/s at the bottom of the hole. Discrete *z*-axis *P*-wave measurements on cores provide an estimate for the interval from the seafloor to the bottom of the drill pipe at 85 mbsf. Combining these data we were able to establish a velocity profile to the bottom of the hole and derive reliable calculations of depths to key reflectors in the seismic data crossing Site U1482.

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