

IODP Expedition 359: Maldives Monsoon and Sea Level

Site U1468 Summary

Background and Objectives

Site U1468 is located in the Kardiva Channel in the Inner Sea at 4°55.9823'N and 73°4.2834'E. This site is the easternmost site of the northern transect, 4.8 km east of Site U1466. At the location of Site U1468, the seismic profiles indicate a succession with the Oligocene/Miocene boundary at 727 msbsf (TWT) followed by the basinal to lower slope deposits of the lower–middle Miocene Kardiva Carbonate Platform. The base of the overlying drift succession (reflection DS1) is a gently basinward dipping horizon. The drift itself is 431 msbsf (TWT) thick, which equals 433 m. The modern current swept seafloor is at 521.45 m water depth.

Site U1468, together with Site U1466, is a key site to constrain the timing of the platform to drift turnover, to date the sequence boundaries of the Kardiva Platform, and to reconstruct the platform evolution from the Oligocene/Miocene boundary onwards. With regard to the drift sequences, the position of Site U1468 was chosen because it bears an extended thickness of the DS1 succession and a greater thickness of DS2 compared to the succession at Site U1466. As the sequences of the mid-Miocene drift succession are likely to be determined by fluctuations of the bottom current regime, dating of such variations and understanding the drift depositional facies will help to address the paleoceanographic objectives of the expedition and the expedition objective to link the changes of the Maldives current regime to global Neogene ocean circulation. The succession recovered at Site U1468 also provides the opportunity to retrieve a complete record of $\delta^{13}\text{C}$ variations in periplatform carbonates through the lower and middle Miocene for establishing a carbon isotopic record that is needed to calibrate this hemipelagic against the pelagic record.

Principal Results

Two holes were drilled at Site U1468. Hole U1468A cored 873.7 m of carbonates using a combination of the APC, HLAPC, and XCB coring systems, with a recovery rate of 53%. Hole U1468B was drilled as a dedicated logging hole with RCB down to 874.7 mbsf. Sediments from a variety of depositional settings were recovered at Site U1468. The top formed a drift package that comprises Lithostratigraphic Units I to IV, while the Miocene

distal slope and the basinal deposits of the Kardiva Platform form Lithostratigraphic Unit V. A restricted basin environment defines Lithostratigraphic Unit VI. Lithostratigraphic Units VII and VIII are shallow water deposits.

Between the seafloor and 45.7 mbsf, Lithostratigraphic Unit I is dominated by a light gray and pale-yellow to white, unlithified to partially lithified packstone to grainstone. Deposits are rich in planktonic foraminifera, and contain abundant benthic foraminifera, ostracods, pteropod fragments, *Halimeda* fragments, mollusk fragments, echinoid fragments and spines, otoliths, fish remains, and very rare bryozoans. Foraminifera and bioclasts are well preserved, and aggregate grains, organic matter, and yellow to brown stained lithoclasts are present. The fine fraction contains aragonite needles (<5 µm), calcite crystals (5 µm to 10 µm), and calcareous nanofossils (coccoliths). Variations in grain size and texture, in particular the gradual change from packstone to grainstone layers, is interpreted as the result of changing current strength.

Lithostratigraphic Unit II between 45.7 and 192.4 mbsf mainly consists of unlithified to partially lithified rudstone to wackestone, with abundant to frequent large benthic foraminifera. The matrix throughout the entire lithostratigraphic unit contains abundant calcite crystals and very rare dolomite rhombs and calcareous nanofossils. Rudstone layers, containing rip-up clasts, other small lithoclasts, echinoid spines and fragments, and other large bioclasts, often form the base of graded beds that have a slight erosional base and fine up to a fine-grained grainstone. Between 192.4 and 296.4 mbsf, Lithostratigraphic Unit III is a light brownish gray to light gray wackestone succession with intercalations of packstone. This unit is characterized by the reappearance of planktonic foraminifera and the disappearance of large benthic foraminifera. Intraclasts are common, indicating early marine cementation and reworking. Most bioclasts are heavily overgrown with dogtooth calcite crystals. The matrix contains abundant calcite crystals, while sponge spicules are minimally present within the fine matrix. Calcareous nanofossils are extremely rare to absent. Lithostratigraphic Unit IV, which consists of a lithified packstone to wackestone, extends from 296.4 to 427.7 mbsf. Components in this unit include bioclastic fragments, as well as planktonic and benthic foraminifera that are severely overgrown by calcite cements. The degree of bioturbation in this unit allows the identification of several ichnotaxa, including *Thalassinoides*, *Palaeophycus*, *Planolites*, and *Chondrites*. Occasionally, some burrows are silicified.

A massive wackestone makes up Lithostratigraphic Unit V between 427.7 and 728.6 mbsf. Throughout the unit, there are alternations of light and dark intervals; the darker color is linked to a higher abundance of organic material. The main components in this unit are planktonic foraminifera, together with benthic foraminifera, mollusk fragments, and bioclast fragments. The components found have calcite cement overgrowth. The well-preserved ichnotaxa identified within this unit include *Thalassinoides*, *Teichichnus*, *Asterosoma*, *Phycosiphon*, *Zoophycos*, *Palaeophycus*, *Planolites*, and *Chondrites*.

Lithostratigraphic Unit VI between 728.6 and 815.9 mbsf is a wackestone to packstone that consists of light gray chalk with intercalations of dark gray to black layers with abundant organic matter. There is an abundance of planktonic foraminifera, and the rock matrix consists of calcareous nannofossils. Lithostratigraphic Unit VII is a layering of wackestone with floatstone intercalations containing large benthic foraminifera *Amphistegina*, *Lepidocyclina*, *Cycloclypeus*, and *Miogypsina*. Lithostratigraphic Unit VIII forms the lowest part of the cored succession at Site U1468. It is a densely cemented limestone that contains abundant shallow-water biota such small and large benthic foraminifera, *Halimeda* plates, bivalve fragments, bryozoan, and coral fragments.

The biostratigraphic analysis of the microflora and microfauna allowed subdividing the succession into four intervals. Interval A was recovered down to ~45 mbsf, and ranges in age from Late Pliocene to Quaternary. The lower part of the Pliocene is missing. The nannofossils are generally sparse with the exception of well-preserved coccoliths in the uppermost sample. The planktonic and benthic foraminifera are moderately abundant in this interval. Interval B extends from about 45 mbsf to 429 mbsf. It comprises middle Miocene to late Miocene calcareous microfossils, which are generally sparse and poorly preserved throughout the succession. One sample, at a depth of 40.59 mbsf, contains a few late Miocene to Pliocene–Pleistocene specimens of planktonic foraminifera mixed with abundant abraded and recrystallized large foraminifera. The base of biostratigraphic interval B corresponds to the base of the drift sequence as determined by the seismic stratigraphy and the lithostratigraphy lithology. Interval C encompasses the middle Miocene to upper Oligocene between 447.3 and 827.4 mbsf with abundant and moderately to well-preserved calcareous nannoplankton. The lowest Interval D contains mainly large benthic foraminifers derived from the fore reef environment.

Geochemical analyses revealed that minimal changes in the $\text{SO}_4^{2-}/\text{Cl}^-$ ratio and alkalinity of the interstitial fluids in the upper 200 mbsf indicate either relatively low rates of organic matter remineralization, or rates of advection by bottom seawater that are faster than the rates of decomposition of organic matter. Below 200 mbsf, there is a net decrease in the concentration of SO_4^{2-} caused by bacterial sulfate reduction. The aragonite concentration in the sediments as measured in XRD remains between 20%–40% throughout the upper 50 m, reflecting variations in input rather than diagenetic change to LMC. The sudden loss in aragonite below ~50 mbsf suggests a period of exposure to fluids which caused partial dolomitization. Neomorphism of the sediments to LMC and some limited amount of dolomitization is indicated by the rapid increase in the $\text{Sr}^{2+}/\text{Ca}^{2+}$ ratio of the pore water below 200 mbsf. Although dolomite formation is supported by the decline in the Mg/Ca ratio of the pore fluid, the present dolomite formation indicated by the pore water data is not responsible for the up to 25% dolomite found in the sediments. This indicates that dolomite must have formed during earlier time periods in a different fluid regime than observed at the present. The large increase in Sr^{2+} in Lithostratigraphic Unit III causes the pore fluids to attain saturation with respect to celestite, which was detected by XRD.

An influence of non-carbonate components upon the pore water chemistry can be seen between 450 and 500 mbsf, where the carbonate content of the sediments decreases to ~80 wt%. Here, the K^+ of the pore waters shows a small increase. The increase in Fe in the sediments and the marked increase in the Mn/Ca ratio below this depth clearly indicate the significance of this transition, which is reflected in a significant reduction in the rate of sedimentation as indicated by biostratigraphic data.

Paleomagnetic analyses show that contamination of the core sediment with highly magnetic material persisted at Site U1468, and it is only slightly attenuated when compared to previous sites. This problem is unambiguously shown by the typical pattern of the NRM intensity that decreases from the top to lower part of each core by three or four orders of magnitude. We noticed that APC and HLAPC cores drilled in the upper part of Hole U1468A seem more affected by this problem compared to XCB cores drilled in the deepest part of the same hole, even though APC cores used non-magnetic core barrels. The distribution of inclinations, despite the large scatter, has a single mode at 0° suggesting that Site U1468 was crossing the equator during the early Miocene.

The strata at this site can be divided into five physical properties units. NGR has the most variability and basically defines the physical properties units but other properties follow the subdivision. For example, in Unit 1 (0–50 mbsf), bulk density is low and porosity is high. At this depth they shift abruptly to higher (density) and lower (porosity) values and subsequently they only show a slight increase and decrease, respectively, to the bottom of the hole. Porosity remains very high even to great burial depth with over 50% porosity at 800 mbsf. Likewise velocity does only display a slight overall increase from Unit 2 through Unit 5 to about 2400 m/s, but high values of up to ~4000 m/s are measured in the more lithified beds. A velocity inversion occurs in Unit 4 that is lithologically the chalk interval of Lithostratigraphic Unit VII.

The color reflectance quantifies the observed cyclic dark-light alternations in the rock but also captures the overall darker tones of Lithostratigraphic Units II and IV. Magnetic susceptibility (MSL) values are like the other magnetic properties impacted by contamination. After filtering erroneous high values, most of the MSL values are very low with a range of –4 to 2 IU, and MSP –15 to –5. Thermal conductivity values increase rapidly from 0.9 to 1.16 W/(m·K) above ~83 mbsf and more gradually below ~83 mbsf to 1.5 W/(m·K) at the bottom of Site U1468 with many fluctuations.

A dedicated logging hole was drilled at Site U1468 to ensure a complete set of downhole measurements. However, during the first logging run with the triple combo tool string, wireline tension increased at 485 m WSF and caliper measurement indicated a narrow borehole of less than 7 inch diameter. These collapsing hole conditions persisted until 280 m WSF, above which the logging run could be completed. No additional logs were run. In the narrow interval of the collapsing hole, the data quality was reduced but the lower and upper portion yielded good data. One characteristic of the logging suite is the low density and the high porosity that is present in the deeper portion of the hole. Measurements on the discrete samples have shown porosities of 40%–50% for most of the logged interval. These high porosities are at the limit of what the tool can read. This might explain the high values of 60%–80% for large portions of the hole.

Based on the electrical resistivity and gamma ray logs, four logging units were identified. Logging Unit 1 that extends from the base of the drill pipe to 201 m WSF is characterized by low gamma ray and resistivity values, both with low to moderate amplitude variability except for two peaks around 190 and 200 m WSF. Logging Unit 1 correlates mostly with

Lithostratigraphic Unit II, which in the logged interval displays an overall coarsening upward trend and textures from mudstone to packstone at the base and grainstone to rudstone at the top. In Logging Unit 2 (201–490 m WSF), the character of the resistivity changes with alternations of lower and higher resistivity over intervals of meters to tens of meters. The gamma ray log is nearly flat except at the base of the unit between 450 and 490 m WSF. This logging unit corresponds to Lithostratigraphic Units III, IV, and part of V. The first two correspond to the drift sediments of drift sequence DS1 that is composed of wackestone with some packstone intervals (Unit III) and lithified packstone (Unit IV). Intervals of higher gamma ray and corresponding resistivity variations at the base of Logging Unit 2, from 450–490 m WSF, capture the alternations of sub-meter to multiple meter scale light and dark intervals deposited at the distal bottomsets of the prograding Kardiva Platform. Logging Unit 3 is entirely within the bottomsets of the prograding platform that is characterized by the alternations of darker and lighter packstones to wackestones. The resistivity log reflects this rather uniform lithology with low variability values that slightly increase with depth. The gamma ray log displays more variability from low to moderate amplitude and also increases with depth. These variations in the gamma ray signature are mostly the result of uranium variations that are likely related to changes in the organic material that varies from the dark (high) to the light (low) intervals. In Logging Unit 4 (720–835 m WSF), the resistivity character changes from low to moderate amplitude. Likewise the gamma ray log exhibits the greatest variability compared to the other units. Again the amplitude and variability of the gamma ray log is mainly caused by the uranium content. Lithologically this unit coincides with the thick Late Oligocene–Early Miocene package of chalky sediment with intercalations of dark organic rich layers. These black layers are taken as indicators of higher productivity and lower oxygenation during times of deposition.

Although no sonic log or vertical seismic profile (VSP) could be run at Site U1468, two high impedance events that were identified by distinct lithology changes in the core helped in building a robust velocity model for the time-depth correlation on the seismic profiles. The first impedance event is generated by the top of densely cemented shallow-water limestone of the Oligocene carbonate platform at 854.7 mbsf (1398 ms TWT) and the overlying wacke-floatstone; the second is a densely cemented grainstone interval with the top surface at 540 mbsf (1198 ms TWT). These two surfaces are used as “check shots” for refining the velocity model.

The penetrated seismic section at Site U1468 displays four main seismic facies. At the bottom are near-horizontal seismic reflections with a distinct high amplitude reflection that corresponds to a lithified bioclastic floatstone at the top of the Oligocene shallow-water carbonate platform, which produces the reflection O/M. The O/M reflection was defined by Belopolsky and Droxler (2004) as the Oligocene/Miocene boundary, but shipboard biostratigraphic analysis of the calcareous nannoplankton and the planktonic foraminifera indicated that the Oligocene/Miocene boundary is located further upsection between 769.74 and 779.36 mbsf (i.e., between horizons O/M and platform sequence PS01). This interval is composed of a nannofossil chalk package with the intercalations of organic rich layers. Above this chalk package are near-horizontal low amplitude reflections that are the distal bottomsets of the Kardiva Platform sequences PS01 to PS11, which encompass the depth intervals from 427.70 to 724.56 mbsf. They are composed of bioturbated planktonic foraminiferal wackestone to packstone with m-thick alternations of darker and lighter layers. Sections of alternating amplitude intensities are likely caused by pulses of deposition and intermittent slow sedimentation and associated diagenesis. The age of these prograding sequences ranges from the Middle Burdigalian to Langhian, or approximately from 21 to 12.7 Ma.

The onset of the drift sequences lies at 434 mbsf and is indicated by wavy high-amplitude reflections. Generally, drift sequence DS1 displays a large mounded geometry with high-amplitude parallel reflections that conjugate basinward. The lower part of the drift sequence DS1 consists of lithified bioclastic packstones to wackestones. Drift sequence DS2 consists of high amplitude slightly inclined seismic reflections, and is composed of a series of unlithified to partially lithified coarsening-upward packages of large benthic foraminiferal grainstone to rudstone. At the top of DS2, the reflections become nearly horizontal, marking the apex of the drift mound that continues into the base of sequence DS9. At Site U1468, the sequence boundaries of DS3 to DS9 merge into two horizontal reflections that are separated only by approximately 20 m. The uppermost drift sequences DS9 and DS10 show undulating high-amplitude reflections and a facies of mud-poor bioclastic packstones and grainstones, similar to the modern seafloor sediments.