IODP Expedition 359: Maldives Monsoon and Sea Level
Site U1471 Summary

Background and Objectives

Site U1471 (proposed Site MAL-07A) is the eastern end of the southern transect at 4°45.9828′N and 73°08.1146′E in a water depth of 419.3 m in the Inner Sea. Geologically the site is positioned on the distal portion of the prograding drift where it thins and is overlain by the sheeted drift deposits. The target depth is in the distal bottomsets of the sea level-controlled platform sequences underneath the drift that was estimated to be about 950 mbsf. At this location, all sequence boundaries are conformable; therefore, cores from this site were expected to provide a continuous and expanded record of current evolution from the Middle Miocene throughout the Pleistocene.

The specific objectives for Site U1471 were: (1) to constrain the age of onset of current-dominated sedimentation; (2) to analyze the cyclostratigraphy of drift deposits, therefore providing reconstructions of changes in the current regime and monsoon cyclicity; and (3) to constrain the timing of sequence boundaries within the drift and the youngest platform sequence.

Principal Results

An 889 m thick succession of drift deposits above a 110.9 m thick distal platform bottomset was retrieved at Site U1471. Seven lithostratigraphic units were distinguished in the drift deposits that reflect the degree of current-controlled winnowing and diagenetic overprint. The eighth lithostratigraphic unit comprises the periplatform deposits in the distal bottomsets. Lithostratigraphic Units I–III (0–180.1 mbsf) consist of planktic foraminifera-rich packstone to wackestone that are heavily bioturbated, often producing a mottled appearance. All contained benthic foraminifera, echinoderm spines, pteropods, sponge spicules, calcareous nannofossils, and mullosk fragments, in addition to the abundant planktic foraminifers. The degree of lithification was used to distinguish the unlithified Unit I from partly lithified Unit II, while the predominance of the wackestone texture was taken as the criteria to separate Unit III. All three units contain alternations of intervals with darker and lighter colors. These alternations range from ~1 to 10 m, where the darker colored portion of the alternation is generally much thinner, i.e.

~20% of the total. The dark intervals are comprised of higher amounts of organic material and tunicates but fewer benthic foraminifera compared to the lighter intervals.

Lithostratigraphic Unit IV (180.1–254.6 mbsf) and Unit V (254.6–588.2 mbsf) have a similar texture and consist predominantly of planktic foraminifera-rich packstone. These units differ in the amount of lithification rather than composition, with alternating lithified and unlithified layers in Unit IV, while Unit V contains densely cemented layers and layers with moldic porosity. Lithostratigraphic Unit IV had some wackestone intercalations that were generally less lithified than the packstone. In both units, overgrowth of bioclasts was prevalent. Several intervals in Unit V exhibit visible porosity, including intraparticle, moldic, and vuggy porosity. At times celestine is present, forming large crystals spanning adjacent pores.

Lithostratigraphic Unit VI was defined by the occurrence of alternations of very fine- to medium-grained dark brownish packstone and dark brownish gray to light gray wackestone/packstone. In addition to planktic foraminifera, sponge spicules, radiolarians, and calcareous nannofossils were identified, as well as rare dolomite crystals. Packstone intervals were thinner than those comprised of wackestone. Packstone intervals became thicker and more prevalent downhole. Packstones were less bioturbated than the wackestones, and individual burrows were discernable and lamination-like structures are present. The burrows are in some cases completely flattened, and some of the non-continuous lamination-like structures may be highly compacted burrows, possibly with organic matter. *Planolites, Chondrites*, *Palaeophycus, Phycosiphon, Thalassinoides, Teichichnus,* and *Zoophycos* ichnofossils were identified, in that order of abundance. Fractures in incompletely cemented beds occur as both open and cemented fractures.

Lithostratigraphic Unit VII contained thin, loosely cemented grainstone layers in a background sediment of fine-grained foraminifera-rich packstone. The light brownish gray to light gray coarse-grained bioclastic-rich grainstone had thicknesses between 2 and 78 cm (average 14 cm). They often (but not always) had sharp lower boundaries and a more gradational top. The grain size did not vary much within the grainstone layers. These layers were interpreted as high-energy current events within this first drift sequence.

In the distal bottomsets of the prograding clinoforms of lithostratigraphic Unit VIII, the facies changed considerably from very fine- to fine-grained, white to light gray, foraminifera-rich packstone to wackestone and very fine-grained and finer dark gray wackestone to mudstone. Calcareous nannofossils were abundant in both end members; planktic foraminifera were abundant in the brighter packstones to wackestones and rare in the dark wackestones to mudstones. Benthic foraminifera and glauconite were present only in the brighter packstones to wackestones. In the brighter intervals, bioturbation was common with ichnofossils including *Planolites*, *Thalassinoides*, *Zoophycos*, and *Chondrites*.

Biostratigraphic and paleoenvironmental analyses were conducted in Holes U1471A, U1471C, and U1471E, and provide a robust age model at Site U1471 in the expanded section of younger drift sequences and the top of underlying bottomsets. Pleistocene and Late Pliocene sediments extend from the seafloor to ~150 mbsf and are defined by a succession of well-constrained events and reasonably good agreement of the data. The implied sedimentation rate is 4.0 cm/k.y. However, there is a consistent offset between the ages inferred from calcareous nannofossil events and those from planktonic foraminifers, with the planktonic foraminifers suggesting ages about 0.5 Ma older than the calcareous nannofossils. This pattern was also seen in this interval in Sites U1465, U1466, and U1467, so possibly the age calibrations of these events may need revision, at least for this area.

In the early Pliocene to middle Miocene sediments and rocks within the top of underlying bottomsets, preservation of planktonic foraminifers is generally moderate to very poor, with mostly poor to very poor preservation in the samples from Hole U1471E. Benthic foraminifers are moderately preserved throughout this interval, with preservation decreasing downhole. Nannofossil preservation was poor to moderate through most of the core. In the lower part of Hole U1471E (Cores 37R–44R), nannofossils were generally more abundant and better preserved. The planktonic foraminiferal and nannofossil events recognised in this early Pliocene to mid-Miocene section agree reasonably with each other and provide an inferred sedimentation rate of 8.0 cm/k.y.

The concentrations of major anions and cations in interstitial water of the upper 40 mbsf exhibited negligible changes, reflecting either low rates of organic matter remineralization or fast rates of advection by seawater. Below this interval, pore water

profiles of many elements started to vary, indicating numerous diagenetic processes occurring in the sediment column. The inflection points of these profiles, however, did not coincide with boundaries between lithostratigraphic units.

A decrease of sulfate coincided well with an increase in alkalinity, indicating that bacterial sulfate reduction is occurring in the sediment column. However, a greater increase in alkalinity was expected from the ~4 mM decrease in sulfate than was observed; the difference was explained by the authigenic precipitation of calcite. The decrease in Mg^{2+} and concurrent increase in Ca^{2+} reflects dolomitization by replacement of calcium carbonate. However, only a minor amount of dolomite was found at this site, with the dolomite peak at 105.55 mbsf occurring close to the maximum decrease in Mg^{2+} concentrations. A rapid increase in the Sr^{2+}/Ca^{2+} ratio of the pore water occurs below 40 mbsf, documenting the neomorphism of aragonite sediments to low magnesium calcite, which was also evident in the changes in carbonate mineralogy based on the XRD data. The large increase in Sr^{2+} caused the pore fluids to attain saturation with respect to celestine ($SrSO_4$). The presence of celestine based on XRD spectra and high sedimentary Sr/Ca ratios extends to approximately 700 mbsf. Changes in the Mn content of the pore waters and the sediments were related to the redox state. The higher Plio–Pleistocene Mn/Ca and Fe/Ca ratios may reflect a more reducing environment during this time interval relative to the Late Miocene. The small increase in Mn/Ca and Fe/Ca in the Middle Miocene may be coincident with the development of the oxygen minimum zone (OMZ).

A cyclic pattern in carbonate content was visible when the data are smoothed with a 5-point moving average, with alternations of ~5 wt% between higher and lower values. The upper 300 mbsf had a period of ~40 m, with 7 or 8 maxima within this depth interval. Where recovery was poor, from 300 to 400 mbsf, the smoothing was not effective, but cycles with an amplitude of ~5 wt% carbonate were again apparent between 400 and 1000 mbsf. The apparent cycles in carbonate content may be related to changes in climate or currents, which influenced sediment supply at Site U1471.

For establishing a magnetostratigraphy at Site U1471, the core orienting device was used in the upper 19 cores drilled from Hole U1471C and in Cores 6H and 7H in Hole U1471D. The magnetostratigraphy is based on the interpretation of the declinations in the

oriented APC cores that show relatively consistent directions within each core, with most of the reversals occurring within a single core.

The Brunnes/Matuyama boundary was tentatively placed between Cores U1471C-4H and U1471D-6H (36 to 39 mbsf), based on the short reversal found in Core U1471D-5H, which was interpreted as the Jaramillo event. Additional reversals were identified at 79, 84, 112, 152, 169, and 172 mbsf (Cores U1471C-9H, U1471C-10H, U1471C-12H, U1471C-16H, and U1471C-19H). For the unoriented cores of Hole U1471A, a smoothing moving average (6 points) in the inclination was performed and a series of magnetozones were defined as intervals with multiple, consecutive sections with the same polarity. The magnetostratigraphy based on inclination only, however, has a high degree of uncertainty because of the subequatorial paleolatitude of Site U1471.

The analysis of the physical properties allowed dividing the sedimentary formation into six units, mainly based on the measurements of porosity and natural gamma radiation. In Unit 1 (0–68 mbsf), sediments have high porosity values of 60%–75% decreasing downhole within the unit. Porosity, however, increases again downhole in Unit 2 (68–138 mbsf) to reach values of 75%. A similar reversal of the porosity trend again occurs in the lower part of the succession in Unit 6 (700–1003 mbsf), where porosity values reach around 50% and are on average higher than in Unit 5 (320–700 mbsf). Natural gamma ray counts in some intervals reached values higher than 80 cps (Unit 4, 180–320 mbsf), which are the highest values measured on the cores of Expedition 359.

Three logging runs were conducted at Site U1471, but only the triple combo tool string reached the bottom of the hole. The Versatile Seismic Imager (VSI) tool string encountered an obstruction at ~615 m WSF, as did the sonic tool string at 454 m WSF. The triple combo tool string produced good quality data except in three intervals where the borehole diameter was too large. The gamma ray values are dominated by uranium, as has been seen at all other sites. The porosity log confirmed the high porosities measured in the laboratory and confirmed unusual high porosities of the drift deposits. Resistivity and magnetic susceptibility display similar trends and show a slight increase downhole with two intervals with high and variable values between 50 and 400 m WSF. They decrease from there to the bottom of the hole but had a small but abrupt decrease at the bottom of the drift. In the short interval, the measured velocity displayed a gradual increase with depth to 400 m WSF with a few higher peaks. In the deepest 40 m of the

log data (400 to 440 m WSF), velocity fluctuated dramatically and reached as high as 3.5 km/s. These fluctuations match the alternating lithified and unlithified lithologies observed in the cores. Four formation temperature measurements documented a low geothermal gradient of 15.3°C/km.

Determining the relative positions of core gaps among the various holes at Site U1471 during coring was accomplished by using GRA data collected at 5 cm resolution on the Whole-Round Multisensor Logger (WRMSL). Natural gamma radiation was also used to evaluate sedimentary completeness among Holes U1471A, U1471C, and U1471D. High-resolution compositing was based on the 2.5 cm interval color reflectance parameter L* for all but one interval where L* lacked distinct patterns. The composite depth scale and splice at Site U1471 are constructed from 0.0 to 195.71 m (CCSF-D), below which cores from Hole U1471A are appended with a constant affine value.

The top 30 m of the L* records from Sites U1467 and U1471 were compared to assess late Pleistocene sections at each site. This interval was correlated to 0–800 ka at Site U1467. Based on the L* records, the latest Pleistocene is slightly more expanded at Site U1467 relative to Site U1471 over the interval correlated to Marine Isotope Stages (MIS) 1–11. Below this level, the reflectivity L* highs are more expanded at Site U1471 relative to Site U1467. The change in relative thickness of the reflectivity highs between Sites U1467 and U1471 sedimentation may indicate subtle changes in the location of current controlled sedimentation at ~450 ka.

The seismic stratigraphy and the core data were correlated using three stations of the check shot survey with the VSI tool string in the upper part of the hole. To anchor our velocity model in the part below 604.6 mbsf where hole collapse prevented further lowering of the tool, we used the lithological boundary between Lithostratigraphic Units VII and VIII (Core U1471E-33R) that marks the change from the drift to the platform sequences at 898 mbsf as a tie point. The three oldest drift sequences DS1 to DS3 at Site U1471 show a pronounced clinoform prograding reflection pattern. Sequences DS5 to DS10 were classified as elongated mounded separate drifts. Site U1471 penetrated the bottomsets of the prograding drift bodies, calibrating the seismic facies with the depositional facies. For example, high-amplitude reflections, especially in sequence DS3, are related to strong impedance contrasts and were produced by the alternation of partly

lithified and lithified beds. In sequence DS3 and DS4, small-scale wavy reflections are interpreted as cyclic steps or bottom current related features.

The correlation of the seismic sequences and the biostratigrpahic age model shows the sequence DS9 encompasses the Pleistocene. The pronounced change in lithology between Lithostratigraphic Unit IV–V at 254.6 mbsf correlates with the base of DS4 (261.5 mbsf) and roughly coincides with the boundary between the Pliocene and Miocene. The bottom of the drift that is the base of DS1 at 898 mbsf was lithologically expressed by a color change from grayish brown tones to dark gray and white alternations and the last occurrence of grainstone layers at 898 mbsf in the late Middle Miocene.