IODP Expedition 355: Arabian Sea Monsoon

Site U1456 Summary

Background and Objectives

Site U1456 (proposed Site IND-03C), the first drill site of IODP Expedition 355, lies within the Laxmi Basin in the eastern Arabian Sea (16°37.28′N, 68°50.33′E) in 3640 m of water. The site is situated ~475 km west of the Indian coast and ~820 km south from the modern mouth of the Indus River, which is presumed to be the primary source of sediments to the area, at least since the Neogene and likely since the Eocene (Clift et al., 2001).

The Laxmi Basin is flanked to the west by Laxmi Ridge and to the east by the Indian continental shelf. The nature of the crust in the Laxmi Basin has been the subject of vigorous debate. Some workers have proposed that it is stretched continental crust (Miles et al., 1998; Todal and Eldholm, 1998; Krishna et al., 2006), based on the reduced crustal thickness in the Laxmi Basin (~6–7 km) compared to the neighboring thicker crust on either side (up to 17 km under Laxmi Ridge) (Misra et al., 2015). In this model the Laxmi Ridge would be a continental fragment rifted from peninsular India (Naini and Talwani, 1983; Talwani and Reif, 1998; Minshull et al., 2008). In contrast, some workers interpret the Laxmi Basin to be of oceanic affinity based on asymmetrical magnetic anomalies within the basin. Such a model relates these magnetic anomalies to the early phases of seafloor spreading in the Arabian Sea (Bhattacharya et al., 1994; Pandey et al., 1995), which removed a micro-continental Laxmi Ridge block from mainland peninsular India. In this case the Laxmi Basin would be more similar to its along-strike equivalent in the Gop Rift to the northwest.

Since the time of continental breakup at the end of the Cretaceous, the Laxmi Basin has been largely tectonically inactive as seafloor spreading has migrated away towards the southwest of Laxmi Ridge (Royer et al., 2002). The regional seismic data from this region suggest that the process of post-rift thermal subsidence has been interrupted by localized magmatic intrusions but there has been no strong deformation of the basin since the end of extension, estimated to be prior to ~65 Ma based on magnetic anomalies within the basin (Bhattacharya et al., 1994) or before 63 Ma based on the timing of onset of seafloor spreading west of Laxmi Basin (Chaubey et al., 2002). Although Laxmi Basin is separated from the main Arabian Sea by the topographic high of Laxmi Ridge, it has nevertheless been supplied by sediment from the Indus River and forms the easternmost part of the Indus submarine fan, the second largest such sediment body in the modern oceans. Proximity to peninsular India means that the basin has been the recipient of some sediment discharge from rivers flowing to the west coast of the subcontinent, most notably the Narmada and Tapti Rivers, although their discharge is much less than that seen in the Indus River. Milliman and Syvitski (1992) estimated 125 and 250 × 10^6 t/yr for the Narmada and the Indus, respectively, in recent times.

Site U1456 is the focus of a number of scientific objectives central to IODP Expedition 355. Sampling and dating the base of the Indus Fan is a primary objective of this expedition. The proposed deep penetration at Site U1456 was aimed at revealing the Cenozoic evolution of the Indus Fan with the intention of reconstructing the weathering and erosion history of the western Himalaya. Sediment recovered at this site should allow us to reconstruct patterns and rates of erosion, as well as to constrain how and when continental environmental conditions changed (e.g., humidity and vegetation patterns) in the Indus drainage since the onset of India-Asia collision. In particular, we aim to test the hypothesis that the exhumation of the Himalaya was driven by the changing strength of the summer monsoon precipitation. For instance, increased erosion along the southern flank of the Tibetan Plateau in response to a stronger monsoon rainfall allowed the Greater Himalaya to be exhumed (Clift et al., 2008). Direct coupling of erosion rates and exhumation is a prediction of the popular “Channel Flow” model for Himalayan evolution (Beaumont et al., 2001; Hodges, 2006). Such coupling would also be applicable to some tectonic wedge models for structural evolution (Robinson et al., 2006) and is not unique to the Himalaya (Willett, 1999). Because Site U1456 is located in the distal fan and we estimated reasonably high sedimentation rates based on seismic ties to industrial wells with age control on the outer western continental shelf of India, the site was also designed to document high-resolution changes in weathering, erosion and paleo-environment during the Quaternary that can be related to millennial-scale monsoonal changes linked to solar and ice-sheet related forcing.

In addition to the objectives related to Cenozoic evolution of the Indus Fan, Site U1456 was also planned to address questions pertaining to the nature of the basement of Laxmi Basin. In order to test the hypotheses of whether Laxmi Basin is oceanic or continental, we need to directly sample the basement underlying the basin, which has significant implications for the break-up history of India and the Seychelles. In addition, analyses of sediments retrieved from the Laxmi Basin will allow us to constrain depositional conditions in a rifted basin. Such sediment may be used to reconstruct vertical tectonic motions and so determine the response of the lithosphere to the pre-, syn-, and post-rift tectonic stresses associated with continental break-up.

At Site U1456, we planned to core to ~100 m into basement through the base of the Indus Fan to address the primary expedition objectives. However, because of technical difficulties encountered when drilling the complex lithologies within a mass transport deposit emplaced in the basin during the Miocene, we were forced to terminate coring in the deepest hole of this site at ~1109 m below seafloor (mbsf), well above the target depth of ~1590 mbsf. The cored section at Site U1456 includes expanded upper Miocene to recent strata punctuated by several hiatuses. Nonetheless, using the samples and data generated at this site, we will be able to address the questions related to changes in the monsoon at ~8 Ma, as well as how monsoon intensity varied after the onset of Northern Hemisphere Glaciations. In addition, we cored through ~350 m of mass transport deposit that likely represents the largest known deposit of this type in the geological record (Calvès et al., 2015). Studies focused on this interval will help to identify the source of these deposits, as well as examine how such large deposits are emplaced, and may help us to understand the mechanism through which they are formed.

Operations

After a 941 nmi transit from Colombo, Sri Lanka, the vessel stabilized over Site U1456 at 1054 h (UTC + 5.5 h) on 9 April 2015. We cored five holes at Site U1456 (IND-03C). The original operations plan called for three holes: the first to advanced piston corer (APC) refusal, followed by a second APC hole with extended core barrel (XCB) coring down to ~650 mbsf. The third hole was a planned reentry hole including 650 m of casing, followed by coring to a total depth of ~1590 mbsf, which included 100 m of basement. The plan was modified to include a short APC hole for high-resolution microbiological and geochemical sampling of the upper ~30 m of section.

When APC refusal was reached at a much shallower depth than anticipated (at ~140 mbsf), we opted to deepen Hole U1456A using the half-length APC (HLAPC). Because of good hole conditions, we continued coring in Hole U1456A with the XCB to

426.6 mbsf when the XCB cutting shoe detached and was left in the hole, forcing us to abandon the hole. Hole U1456B was cored with the APC to 29.1 mbsf. We then cored Hole U1456C with the APC and HLAPC to 221.6 mbsf, drilled ahead without coring to 408.0 mbsf, and then continued coring with the XCB to 465.2 mbsf. We terminated coring operations at Hole U1456C when we determined that the lithology at 465.2 mbsf would be ideal for the base of the casing for our deep hole. After conditioning the hole for logging, we conducted three logging runs in Hole U1456C. The triple combo was run first without the radioactive source to 465 m wireline depth below seafloor (WSF), and then the Formation MicroScanner (FMS)-sonic to 465 m WSF with two up-passes. The last logging run was made with the triple combo tool suite with the radioactive source after the hole was determined to be in good condition.

In Hole U1456D, we drilled in a 10¾ inch casing string to 458.8 mbsf and then began coring with the rotary core barrel (RCB) coring assembly. When we reached 1024.2 mbsf, we pulled out of the hole for a bit change; however, we encountered difficulties reentering the hole. The drill string then became stuck in the open hole below casing and ultimately had to be severed, effectively terminating the hole. We then decided to install a longer 10¾ inch casing string to 748.2 mbsf in Hole U1456E, drilled without coring to 970 mbsf, and then continued to RCB core to a depth of 1109.4 mbsf. We pulled out of the hole for a bit change and again encountered difficulties trying to trip the drill string back to the bottom of the hole. After little progress was made to advance the bit over a 12 h period and several instances of the drill string getting temporarily stuck, we decided to terminate the hole and end operations at Site U1456. The total time spent on Site U1456 was 885 h (36.9 days).

A total of 197 cores were collected at this site. The APC coring system was deployed 35 times, recovering 276.91 m of core over 301.9 m of penetration (92% recovery). The HLAPC system was deployed 72 times, recovering 287.55 m of core over 334.8 m of penetration (86% recovery). The XCB coring system was deployed 13 times, recovering 44.58 m of core over 94.3 m of penetration (47% recovery). The RCB coring system was deployed 77 times, recovering 401.63 m of core over 705.0 m of penetration (57% recovery).

Principal Results

The cored section at Site U1456 is divided into four lithologic units based on a compilation of Holes U1456A through U1456E. Lithologic Unit I consists of an ~121 m thick sequence of Pleistocene light brown to light greenish nannofossil ooze and foraminifer-rich nannofossil ooze interbedded with clay, silt, and sand. These sandy layers show normal grading and sharp erosive bases and are interpreted as distal, basin plain turbidites. The hemipelagic nannofossil ooze and nannofossil-rich clay show intense burrowing and also include common pyrite concretions. Quartz, feldspar, and mica grains are common in Unit I, whereas heavy minerals are rare in abundance but when they are seen these include hornblende, kyanite, tourmaline, augitic clinopyroxene, apatite, and glauconite. Lithologic Unit II is approximately 240 m thick and is dated to the late Pliocene to early Pleistocene. It consists mainly of massive dark grayish to blackish sand and silt, interbedded with thin-bedded nannofossil-rich clay. These sediments also show normal grading and common sharp erosive bases, which are interpreted as a series of turbidites, likely deposited in a sheet lobe setting. Unit II contains similar sets of light and heavy minerals as in Unit I, although the heavy minerals are more abundant in this unit. The presence of diagnostic high-pressure sodic amphiboles (glaucophane) and pink-green hypersthene is distinctive of Unit II and indicative of erosion from the Indus Suture Zone, The only known source of blueschists is from the suture zone in Kohistan where they are exposed along the Main Mantle Thrust (Anczkiewicz et al., 2000) and would have to be delivered to the main stream via the Swat and Kabul Rivers from the west.

Upper Miocene to upper Pliocene Lithologic Unit III is approximately 370 m thick and mainly consists of semi-indurated to indurated light brown to dark green clay/claystone, light brown to dark gray sand/sandstone, light greenish nannofossil chalk, and light to dark greenish gray nannofossil-rich claystone. Clay/claystone and sand/sandstone cycles of sedimentation are separated by intervals dominated by nannofossil chalk and nannofossil-rich claystone. Sand layers typically have sharp erosive bases and normal grading into the clay-rich intervals. Low recovery in this unit makes it harder to assign a depositional setting but the turbidites may have been deposited in a sheet lobe. The lower part of Unit III contains common wood fragment layers (up to ~1 cm thick). Bioturbation is mostly limited to intervals of nannofossil chalk and nannofossil-rich claystone. The mineral assemblage of the silt fraction observed under the microscope is similar to that of

Unit II, but heavy mineral abundances are different in the clay fraction. The assemblage is typical of erosion from the Greater Himalaya (Garzanti et al., 2005), but glaucophane is not observed.

Miocene Lithologic Unit IV is approximately 380 m thick and consists of a mixture of interbedded lithologies dominated by dark gray massive claystone, light greenish massive calcarenite and calcilutite, and conglomerate/breccia, with minor amounts of limestone, especially toward the base of the unit. A variety of deformation structures including microfaults, soft-sediment folds, slickensides, and tilted to vertical bedding are observed in this unit. The most common minerals in Unit IV are quartz and micas, with trace to very rare amounts of heavy minerals. Clasts of vesicular volcanic rock and shallow-water limestone in the breccia point to a source on the Indian continental shelf (Biswas, 1987; Whiting et al., 1994), with possible erosion from the Deccan Plateau province. No significant sediment supply from the Indus River is found in this unit, except for a 2 m thick sandstone and claystone bed at the base of the mass transport deposit. This suggests that an early to middle Miocene Indus submarine fan was active in the area at that time.

Calcareous and siliceous microfossils recovered at Site U1456 are typical of subtropical to tropical assemblages. Diatoms and radiolarians are only found in the mudline and uppermost cores from this site, whereas calcareous nannofossils and planktonic foraminifers occur in varying numbers throughout the succession. Diatoms in the mudline samples are well preserved and consist mainly of coastal species, whereas these taxa are absent in the cored sediment. Diatoms are sparse and moderately preserved in the uppermost 10 mbsf and the assemblage includes benthic and freshwater taxa that indicate transport to the site. Radiolarians are very rare, but well preserved in the upper 120 mbsf and absent below. Abundance and preservation of calcareous nannofossils and planktonic foraminifers depends on lithology. In general, calcareous nannofossils are moderately to well preserved throughout Site U1456, whereas planktonic foraminifer preservation varies from poor to good. Both groups are common to abundant in Lithologic Unit I. Nannofossils are sparse and foraminifers usually absent in the coarse-grained intervals of Units II and III. Reworked Cretaceous and Paleogene nannofossils are common through Units I–III. In Lithologic Unit IV, nannofossil and foraminifer abundance varies significantly, from absent to abundant and is characterized by mixed Paleogene to early Neogene taxa that hamper age interpretation.

The age model for Site U1456 is based on calcareous nannofossil and planktonic foraminifer biostratigraphy, together with magnetostratigraphy. The succession of bioevents indicates that Site U1456 spans the lower to middle Miocene to recent, but is punctuated by several hiatuses of varying duration. The Indus submarine fan sediment at the base of the succession contains a nannofossil assemblage characteristic of early to middle Miocene. The mass transport deposit of Lithologic Unit IV appears to have been rapidly emplaced in the late Miocene based on the presence of late Miocene nannofossils within two short hemipelagic intervals within the transported unit. After deposition of the mass transport deposit, the sedimentation rate appears to have been relatively consistent in the late Miocene at ~10 cm/k.y., although deposition was interrupted for ~0.5 m.y. between ~8 and 9 Ma. Another hiatus spanning ~2 m.y. encompasses the Miocene/Pliocene boundary. The sedimentation rate in the late Pliocene to early Pleistocene was again ~10 cm/k.y. After a 0.45 m.y. hiatus, sedimentation rates in the early Pleistocene are much higher (~45 cm/k.y.) during deposition of Lithologic Unit II. The sedimentation rate slows down from the late early Pleistocene to Recent, averaging approximately 12 cm/k.y.

Geochemical measurements at Site U1456 aimed to characterize the distribution of hydrocarbon gases, sediment geochemistry (including carbon, nitrogen, sulfur, and carbonate contents), and interstitial water compositions. Sulfate concentration in the interstitial water decreases sharply in the top 60 mbsf, indicating anaerobic sulfate reduction. Below the sulfate reduction zone, methanogenesis becomes an important process, which is reflected by the increase in methane concentrations between 60 and 120 mbsf. Methane concentrations decrease to ~2000 ppmv near the boundary between Lithologic Units I and II, and then reach maximum values within Unit II. This pattern could be controlled by lithology, with gas accumulating in the relatively porous silty sand and silt with sand layers in Lithologic Unit II, which are capped by the nannofossil-rich clay of Unit I.

Alkalinity, ammonia, and phosphate in the interstitial waters are produced as a byproduct of organic matter degradation in the upper 60 mbsf, within the sulfate reduction zone. Increased alkalinity in this interval causes calcium and magnesium to precipitate as carbonate, resulting in a decrease in calcium and magnesium concentration. Manganese concentrations also decline sharply in the top 70 mbsf within the sulfate reduction zone, where hydrogen sulfide is produced. Iron is consistently low over this interval and may be removed, together with manganese, via metal sulfide formation under anaerobic conditions. The boron concentration profile shows an inverse relationship with that of manganese, suggesting that the adsorption/desorption reaction is the primary control over the boron concentration. Silica concentrations are higher (300–520 µM) in the top 120 mbsf, which may be caused by its release during the dissolution of biogenic silica, which is consistent with near-absence of siliceous microfossils over this interval. Barium concentration increases between 250 and 450 mbsf, which could suggest high organic matter diagenesis through this interval.

Total carbon and $CaCO_3$ content are variable at this site and show similar variations, indicating that most of the carbon is present as $CaCO_3$. Carbonate content is generally higher in Lithologic Unit I, particularly in the nannofossil ooze and nannofossil-rich clay (60–80 wt%). Carbonate content is lower (10–30 wt%) in the silt and sand intervals of Unit I, and throughout most of Units II and III, which are dominantly siliciclastic. Very high carbonate content (70–90 wt%) below 975 mbsf in Unit IV corresponds to the presence of calcarenite, calcilutite, and limestone. Total organic carbon (TOC) values at Site U1456 mostly vary between 0 and 2 wt%, with a few higher values in Unit IV. We report TOC/total nitrogen (TN) as a preliminary estimate for the source of organic material. In Unit I, three distinct intervals with high terrestrial contribution correspond to beds of silty sand with nannofossils and silt with sand. Low TOC/TN values suggest primarily marine to mixed sources of organic matter (Muller and Mathesius, 1999) in Units II and III. Unit IV is characterized by high variability, with very high values within the interval 970–1105 mbsf suggesting strong terrestrial input of organic matter. Correlation between TOC and total sulfur provides a further general estimation of the source of organic matter in marine sediments (Berner and Raiswell, 1983) and is consistent with the interpretations based on the TOC/TN.

A total of 72 whole-round samples (5–10 cm long) were collected for microbiological studies at Site U1456. These samples were taken adjacent to interstitial water whole-round samples for comparison to interstitial water chemistry. Samples were mostly preserved for postcruise characterization of the microbial population using DNA/RNA, as well as lipid and cultivation-based studies. Fluorescent microspheres were added to the core catcher sub before the core barrel was deployed during APC coring to use as a contamination tracer. Samples were collected from the exterior, interior, and an intermediate position from each of the whole-round samples to determine the potential extent of contamination. Examination of the microsphere content of these samples was carried out on board and indicates that samples from the exterior contain higher concentrations of microspheres than those from the intermediate position. Microspheres were completely absent in samples from the interior of the cores, indicating no apparent contamination of the interiors of these cores. Some samples were also analyzed for new microbial community structures. The subsurface sediments (0–27 mbsf) from Hole U1456B contain many specimens of eukaryotic species (fungi) and deep marine invertebrates (meiofauna). Additional analyses are required to pinpoint the phylogenetic positions of these new taxa, which will be addressed during postcruise research.

Paleomagnetic analyses on Site U1456 cores produced a magnetic polarity stratigraphy defined on the basis of inclination data as core orientation attempts met with mixed success. A composite polarity log was constructed from detailed demagnetization experiments on discrete samples from Holes U1456A, U1456C, and U1456D. The polarity log was correlated with some confidence to the geomagnetic polarity time scale with a total of 12 tie points. These ranged from the Brunhes (Chron C1n, beginning at 0.781 Ma) to the top of Chron C5n (9.786 Ma). In collaboration with biostratigraphic results, we identified three substantial hiatuses. The youngest spanned from within C2n to the top of C2An.1n. The second spanned all of C3n to the top C3An, and the third eliminated C4n through part of C4r.

Rock magnetic studies were carried out on samples from Holes U1456A and U1456D and point to a complex array of magnetic minerals including iron sulfides (greigite) and iron oxides (magnetite, maghemite, and hematite). No behavior indicative of goethite was observed. Further study is necessary to determine which minerals are likely detrital (with the potential of constraining weathering on the continent) and which formed during diagenesis.

The physical property data collected for Site U1456 includes *P*-wave velocity, bulk density, magnetic susceptibility (MS), and natural gamma radiation (NGR) on whole-round cores from Holes U1456A to U1456E and additional measurements on split cores and discrete samples including thermal conductivity, shear strength, *P*-wave velocity, porosity, and bulk, dry, and grain densities. Acquired data correlate with lithology, composition, and induration of the recovered section. Bulk density, *P*-wave velocity, shear strength, and thermal conductivity generally increase with depth from 0.8 to 2.4 g/cm^3, 1500 to 3400 m/s, 10 to 220 kPa (at ~360 mbsf), and 0.8 to 2.0 W/(m·K), respectively, whereas porosity decreases from nearly 80–50% at 150 mbsf to ~20% at the base of the recovered section. This indicates that sediment compaction plays a significant role in physical property variations.

Lithologic changes are apparent in variations in NGR and MS, which range from 10 to 80 cps and 0 to 400 SI units, respectively. Carbonate sediments have low NGR activity (10–35 counts/s average) and low magnetic susceptibility (0–20 SI units) and are dominant in Units I and the lower part of Unit IV (below ~975 mbsf). Detrital sediments (such as sand, sandstone, clay, and claystone) that are abundant in Unit II have much higher average NGR activity (50–80 counts/s average), magnetic susceptibility (50–150 SI units), and bulk density (1.8–2.0 g/cm^3) than those of Lithologic Unit IV. Units III and the upper part of Unit IV show variable NGR, but generally lower and less variable MS than the other units. The grain density varies between 2.75 and 3.0 g/cm^3 with no visible downcore trend except for characteristically low and consistent values of 2.7 g/cm^3 in the lower part of Unit IV. Shear strength indicates that sediments range from soft (0–50 kPa) above 200 mbsf to stiff (150–220 kPa) from 200 to 360 mbsf, below which core material has a shear strength >220 kPa.

Two downhole logging tool strings were run in Hole U1456C, the triple combo (NGR, porosity, density, electrical resistivity, and MS) and the FMS-sonic (NGR, sonic velocity, and electrical resistivity images). All runs reached the total depth of the hole at 465 m WSF. Borehole log quality was affected by an enlarged borehole above 200 m wireline matched depth below seafloor (WMSF) and large and rapid variations in borehole size between 370 and 200 m WMSF. Below 370 m WMSF, the hole diameter was mostly in-gauge, with few washed out zones. Lithologic variations are apparent in the NGR, bulk density, porosity, and magnetic susceptibility logs, and these correlate well with measurements made on the recovered cores from Holes U1456A and U1456C. There is a trend of increasing density and sonic velocity from the top of the logs at ~80 mbsf to the bottom of the hole due largely to compaction and cementation with depth. A large increase in natural gamma radiation and bulk density occurs between Logging Units 2 and 3, which correlates to an increase in grain size from clay to silt and sand. Formation temperature measurements made with the APCT-3 on Cores 355-U1456A-7H, 10H, and 13H indicate a geothermal gradient of ~57°C/km for the upper ~120 mbsf.

Distinctive changes in color, MS, NGR, and GRA bulk density were used to make hole-to-hole correlations between the sediments from Holes U1456A, U1456B, and U1456C. We constructed a spliced section for Site U1456 from the seafloor to a depth of ~142 m core composite depth below seafloor (CCSF). This spliced interval includes the upper Pleistocene (~1.3 Ma) to recent.

We were also able to correlate core data from Holes U1456A and U1456C to wireline logging data collected in Hole U1456C. The NGR signal was sufficiently high that we could make unambiguous correlations between the core data and logs in the interval logged through pipe (0–81 mbsf). Distinctive MS signals were very useful to correlate cores to the logs between 150 and 450 mbsf.

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