IODP Expedition 355: Arabian Sea Monsoon

Site U1457 Summary

Background and Objectives

Site U1457 (proposed Site IND-06B), the second drill site of IODP Expedition 355, lies within the Laxmi Basin in the eastern Arabian Sea (17°9.95′N, 67°55.80′E) in 3534 m water depth. The site is situated ~490 km west of the Indian coast and ~760 km south from the present-day 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. Site U1457 lies on the western side of the basin at the foot of the slope leading to Laxmi Ridge. The seafloor appears to be relatively flat in the vicinity of Site U1457; however, seismic reflection data show that the basement depth gradually increases to the east away from the site. The nature of the crust in Laxmi Basin is an enigma. 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 Laxmi Basin (~10 km) compared to the neighboring thicker crust on either side (up to 17 km under Laxmi Ridge) (Misra et al., 2015) and ~40 km under peninsular India (Singh et al., 2015). In this model, 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 Laxmi Basin to be of oceanic affinity based on magnetic anomalies reported within the basin. This 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 scenario Laxmi Basin would be analogous to its along-strike equivalent in Gop Rift to the northwest and Site U1457 would lie seaward of the oldest magnetic anomaly, requiring Laxmi Basin to be located on oceanic crust.

Since the time of continental breakup at the end of the Cretaceous, Laxmi Basin has for the most part been tectonically inactive as seafloor spreading jumped to the west of Laxmi Ridge after ~62 Ma (Royer et al., 2002) so that the active extension is now far to the southwest. 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 basin of the 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 Fan, the second largest such sediment body in the modern oceans. Proximity to peninsular India means that the basin must have 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 from the Indus River. Milliman and Syvitski (1992) estimated recent loads of 125 and 250 × 10^6 t/y for the Narmada and the Indus Rivers, respectively, although some studies estimate Indus discharge at 675 × 10^6 t/y (Ali and De Boer, 2008). Because Site U1457 is on the western side of Laxmi Basin much of the flux from the Narmada and Tapti Rivers would tend to be ponded on the eastern side or in the central part of the basin.

Site U1457 was originally proposed as an alternate site for meeting our deeper objectives. Sampling and dating the base of the Indus Fan is a primary objective of this expedition. The proposed deep penetration at Site U1457 aimed to reveal the Cenozoic evolution of the Indus Fan with the intention of reconstructing the weathering and erosion history of the western Himalaya. However, pre-drilling seismic interpretation suggested that this record would be truncated compared to that at Site U1456. Nonetheless, sediment recovered at this site should allow a reconstruction of patterns and rates of erosion, as well as constrain how and when continental environmental conditions changed (e.g., humidity and vegetation patterns) in the Indus drainage since the late Miocene. In particular, we aim to test the hypothesis that major changes in the structural evolution of the Himalaya were driven by the changing strength of summer monsoon precipitation. For instance, the southward migration of the main detachment fault to the location of the Main Boundary Thrust after 10 Ma may have accelerated the unroofing of the Lesser Himalayan Duplex and may be linked to the change in monsoon strength around 8 Ma (Huyghe et al., 2001; Bollinger et al., 2004). Because Site U1457 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 paleoenvironment during the Quaternary that can be related to millennial-scale monsoonal changes linked to solar and ice-sheet related forcing.

Because we were unable to sample the basement at Site U1456, Site U1457 was specifically planned to address questions pertaining to the nature of the basement in 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 Laxmi Basin will allow us to constrain depositional conditions in the basin, which 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 U1457, we planned to core ~50 m into basement after penetrating a series of submarine fan sediments, as well as the large mass transport deposit encountered at Site U1456. Drilling was successful in reaching the basement at ~1093 mbsf, although we had time to penetrate only 16.27 m into basement below the sedimentary cover, recovering 8.72 m of basalt. The cored section at Site U1457 includes expanded upper Miocene to recent strata punctuated by some hiatuses or condensed sections. Nonetheless, using the samples and data generated at this site, we should be able to address questions related to changes in the monsoon at ~8 Ma, as well as how monsoon intensity varied after the onset of Northern Hemisphere Glaciation in response to this forcing. This is despite the moderate hiatus that occurs close to this time. In addition, we cored through ~190 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 and comparisons with the thicker section sampled at Site U1456 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 causes of this major event.

Operations

After a 62 nmi transit from Site U1456, the vessel stabilized over Site U1457 at 1330 h (UTC + 5.5 h) on 16 May 2015. We cored three holes at Site U1457 (IND-06B). The original operations plan called for three holes: the first to advanced piston corer (APC) refusal, followed by a second APC with extended core barrel (XCB) coring to ~500 mbsf. The third hole was planned as a single bit rotary core barrel hole (RCB) to 50 m into basement, which was estimated at ~970 mbsf.

In Hole U1457A, we reached APC refusal at ~110 mbsf. In order to deepen the hole more quickly, we opted to alternate coring a 4.7 m interval with the half-length advanced piston corer (HLAPC) with 4.7 m advances without coring. In the interest of time we terminated the hole after reaching 144.8 mbsf. We then cored Hole U1457B for stratigraphic correlation purposes in the upper ~110 mbsf. After reaching APC refusal, we continued with the HLAPC using the core/advance method to 204.7 mbsf where we terminated the hole to preserve enough time to reach our objective in the deep hole. Hole U1457C was drilled without coring to 191.6 mbsf and then cored using the RCB to 1108.6 mbsf, which included ~16 m of basement penetration. Hole U1457C was terminated when time allotted for the expedition expired.

A total of 136 cores were collected at this site. The APC coring system was deployed 24 times, recovering 202.73 m of core over 218.9 m of penetration (93% recovery). The HLAPC system was deployed 15 times, recovering 71.22 m of core over 70.9 m of penetration (101% recovery). The RCB coring system was deployed 97 times, recovering 436.96 m of core over 917.0 m of penetration (48% recovery).

Principal Results

The cored section at Site U1457 is divided into five lithologic units based on Holes U1457A to U1457C. Lithologic Unit I consists of a ~74 m sequence of Pleistocene light brown to light greenish nannofossil ooze including foraminifer-rich nannofossil ooze and nannofossil-rich clay, interbedded with silty clay and silty sand. Unit I is similar to that of Site U1456. The silty sand layers show normal grading and sharp erosive bases and are interpreted as turbidities. The hemipelagic nannofossil ooze and nannofossil-rich clay show intense burrowing and also include common pyrite nodules and veins. Quartz, feldspar, and mica grains are common in Unit I, whereas heavy minerals (hornblende, clinopyroxene, epidote, garnet, and augite) are rare.

Lithologic Unit II is approximately 194 m thick and is dated to the early Pleistocene. It consists mainly of light brownish gray to dark gray silty clay and dark gray sandy silt. Silty clay layers are typically massive and interbedded with very thin gray sandy silt layers, which are interpreted as turbidites. Unit II at Site U1457 is similar in age to Unit II of Site U1456, but the sediments are much finer grained. Light and heavy silt- to sand-sized mineral grains are more abundant in Unit II compared to Unit I.

Unit III is ~450 m thick and consists of upper Pliocene to upper Miocene semi-indurated to indurated light brown to dark green silty claystone, light brown to dark gray silty sandstone, light greenish nannofossil chalk, and light to dark greenish gray nannofossil-rich claystone. Nannofossil chalk and nannofossil-rich claystone cycles of sedimentation are separated by intervals dominated by clay/claystone and sand/sandstone deposition. Strong bioturbation is mostly observed in the nannofossil chalk and nannofossil-rich claystone. Silty sandstone layers are characterized by sharp erosive bases and grade upward into silty claystone intervals. The silty sandstone and silty claystone of Unit III occasionally have very thin (<1 cm) wood fragment layers, as well as large numbers of tiny wood particles. Unit III contains abundant light minerals with variable amounts of heavy minerals.

Miocene Lithologic Unit IV is ~225 m thick and consists of a mixture of interbedded lithologies dominated by dark gray to greenish gray massive claystone, light greenish massive calcarenite and calcilutite, breccia, and limestone, particularly toward the base of the unit. Deformation structures are widespread throughout this unit, including microfaults, soft-sediment folds, slickensides, and tilted to vertical bedding, which are indicative of a mass transport deposit. Light minerals are abundant in Unit IV, whereas heavy minerals are only present in trace amounts. Clasts of vesicular volcanic rock and shallow-water limestone in the breccia point to a source from the Indian continental shelf, with possible erosion from the Deccan Plateau province. The ~30 m thick Paleocene Unit V consists mostly of dark brown to dark greenish gray claystone and dark gray to black volcaniclastic sediment, which overlies the basalt basement. There is a major hiatus between Unit IV and Unit V determined from a combination of biostratigraphy and magnetostratigraphy, as well as the change in facies between debris flow breccia above and mudstone underneath. The dark brown massive claystone shows a very small amount of interbedded dark greenish gray silty claystone, and the thick dark greenish gray claystone contains black, discontinuous manganese layers and nodules, as well as small (1 to 3 cm) gray inclusions and rare parallel bands that are identified as carbonatecemented nodules. Unit V contains trace amounts of light minerals, with no heavy minerals and abundant glass particles.

Core catcher samples and additional samples from split core sections at Site U1457 were analyzed for calcareous nannofossils, planktonic foraminifers, diatoms, and radiolarians. Microfossil assemblages are typical of sub-tropical to tropical water masses. Diatoms and radiolarians are found in the mudline sample in Hole U1457B, where they are well preserved. Diatoms in the mudline sample consist of mainly coastal species that have been transported to the site location. Diatom abundance decreases rapidly downcore, with specimens mostly restricted to the top ~50 cm at Site U1457. Radiolarians are very rare and poorly preserved in the uppermost cores and only occur sporadically below this level.

Preservation of calcareous nannofossils and planktonic foraminifers varies from poor to good throughout Site U1457. Both groups are abundant in Lithologic Unit I. Nannofossils are sparse and planktonic foraminifers usually absent in the clays/claystones that dominate Unit II. In Lithologic Unit III, nannofossils are common in abundance, whereas planktonic foraminifers are less abundant and vary from rare to common. Reworked Cretaceous and Paleogene nannofossils are common through Units I–III. Within Units IV and V, both nannofossils and foraminifers are moderately to poorly preserved with varying abundances. There is also an interval characterized by mixed Paleogene to early Neogene taxa that hamper age interpretation within the lower part of Unit IV. Calcareous nannofossils and planktonic foraminifers are common in the uppermost part of Unit V, but rapidy decrease in abundance downcore through this unit, which overlies the basement.

The chronostratigraphic framework for Site U1457 is based on calcareous nannofossil and planktonic foraminifer biostratigraphy, together with magnetostratigraphy. The succession of calcareous nannofossil and planktonic foraminifer events indicates that Site U1457 spans the early Paleocene through recent, albeit with a very long hiatus (~50 m.y.) between lower Paleocene and upper Miocene sediment. The biostratigraphic framework established at Site U1457 enabled identification of three unconformities and an interval of mass transport in the recovered Neogene section. Calculated sedimentation rates at Site U1457 suggest that the sedimentation rate appears to have been relatively consistent in the late Miocene at ~17 cm/k.y., although deposition was interrupted for ~0.50 m.y. around 8 Ma. Sedimentation rates were somewhat lower after sedimentation resumed following this hiatus, average ~10 cm/k.y. during the remainder of the late Miocene. There is some evidence for a short interval dominated by slower, hemipelagic sedimentation between ~6 and 7.4 Ma. There is an ~2 m.y. hiatus that spans the Miocene/Pliocene boundary and early Pliocene. The sedimentation rate in the late Pliocene to early Pleistocene was ~4 cm/k.y. After another ~0.45 m.y. hiatus in the early Pleistocene, sedimentation rates for the remainder of the early Pleistocene were much higher (~58 cm/k.y.) during deposition of Lithologic Unit II. The sedimentation rate slowed down from the late early Pleistocene to present, averaging approximately 7 cm/k.y.

We cored approximately 16.27 m into igneous basement at Site U1457, recovering 8.72 m of basalt. Texture ranges from aphyric to phyric. The aphyric material occurs in three intervals and consists mostly of altered glass. Phenocrysts vary from absent to up to 10% of the rock and are composed of clinopyroxene, plagioclase, and olivine. Phenocryst grain size ranges from 1 to 5 mm, with a mode of ~3 mm. The ground mass is mostly aphyric and may contain mesostasis. The basalt is nonvesicular and massive and contains veins up to 3 mm in width of variable length that are filled with calcite. These rocks are classified as clinopyroxene-plagioclase-phyric basalt and plagioclase-clinopyroxene-phyric basalt, with the former the more dominant lithology. The basalt is only slightly altered.

Geochemistry measurements at Site U1457 aimed to characterize the distribution of hydrocarbon gases, sediment geochemistry (including carbon, nitrogen, sulfur, and carbonate contents), and interstitial water composition. Sulfate concentration in the interstitial water decreases sharply in the upper 60 mbsf, indicating anaerobic sulfate reduction. Below the sulfate reduction zone, methanogenesis is likely active, reflected by the peak in methane concentrations between 65 and 200 mbsf. A second interval of methane increase is observed between 400 and 550 mbsf, which correlates with Lithologic Unit III. Higher total organic carbon (TOC) wt% values through this interval are indicative of a lithological control to the methane concentrations. Below 591 mbsf, methane levels do not exceed 10,000 ppmv and progressively decrease with depth.

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 helps to precipitate calcium and magnesium in carbonate minerals, resulting in a decrease in calcium and magnesium concentration. Manganese concentrations also decline sharply in the top 60 mbsf within the sulfate reduction zone, where hydrogen sulfide is being produced as a result of anaerobic organic oxidation reactions. Iron concentration is low and decreases downhole, suggesting its removal from the interstitial water through metal sulfide formation under anaerobic conditions. Silica concentrations are high in the top 110 mbsf, which may be caused by its release during the dissolution of biogenic silica, which is consistent with the near-absence of siliceous microfossils in this interval. Barium concentration increases between 250 mbsf and 450 mbsf, which could be a result of its release through barite dissolution under low sulfate fluid conditions or through the leaching of aluminosilicate minerals.

Total carbon and $CaCO_3$ content are highly variable at Site U1457 and are tightly coupled, 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 (20–75 wt%) intervals. A decrease in carbonate content between Lithologic Units I and II reflects a transition to lithologies that are dominantly siliciclastic. High carbonate content intervals (33–47 wt%) in Unit III correspond to intervals of nannofossil ooze. TOC values at Site U1457 vary between 0.02 and 2.58 wt%. We report TOC/TN (total nitrogen) as a preliminary estimate for the source of organic material. Typically high values (TOC/TN >12) in marginal basins are interpreted as an indicator of terrestrial organic input (Muller and Mathesius, 1999). However, an alternative model to explain high TOC/TN ratios, such as those observed in some organic carbon-rich marine sediments (e.g., sapropels and black shales), invokes marine algae synthesizing lipid rich organic carbon during times of abundant nutrient supply and/or diagenetic factors (Meyers, 1997). In Unit I, three distinct intervals with high TOC/TN (>12), correspond to beds of carbonate ooze. The dominantly hemipelagic nature of this lithology precludes confident assignment of the high values to terrestrial input and awaits further shore-based analysis. Intermediate TOC/TN values (4.5 to 11.4) suggest mixed marine/terrestrial organic input from in Unit II and the upper part of Unit III. Low TOC/TN values (0.3 to 8.7) in Unit IV suggest predominantly marine organic matter input between. Due to time constraints, shipboard analyses of samples from Unit V and basement were not conducted.

A total of 12 whole-round samples (5 cm long) were collected for microbiological studies at Site U1457. All samples were collected adjacent to interstitial water whole-round samples for comparison to geochemical analyses. After collection, samples were immediately flushed with N_2 and processed for shipboard analysis or preserved for shore-based analyses. Fluorescent microspheres were used as tracers during APC operations to help determine contamination in microbiology samples. Microsphere samples were collected from the exterior and interior of each core, as well as a location in between. Microspheres were completely absent in samples from the interior of the cores, indicating no apparent contamination. The samples from intermediate positions contained a low concentration of microspheres and the presence of significant numbers of microspheres in exterior samples is a strong indication of surface contamination to the outside of the core during the coring process.

We analyzed some samples on board for microbial community structure. The direct microscopic observation of the core samples found different kinds of meiobenthos in sediments from Site U1457. Preliminary results of microbial community structure and enumeration show that fungal communities are present at very low concentrations in samples from 0 to 100 mbsf. These fungi living in the subsurface form diverse communities and interactions with other living organisms. While surveying for the possibility of symbioses between fungi and meiobenthos, we found abundant assemblages in certain zones showing that these may follow trends related to the carbon, nitrogen, and sulfur cycles. Shore-based molecular studies are required to support the evidence of their relationship and to pinpoint exactly the phylogenetic positions of these new extremophiles.

At Site U1457 we performed paleomagnetic analyses on archive-half sections from Holes U1457A and U1457B, and on discrete samples from all holes. Archive-half section measurements produced reliable results for the upper ~60 mbsf; results were more ambiguous in the deeper sections. Discrete samples were fully demagnetized by alternating field treatment and the inclination of the magnetization’s stable component was used to define the magnetostratigraphy. A composite polarity log was constructed from the three holes and correlated with some confidence to the geomagnetic polarity time scale with at least 16 tie points, which range from the Brunhes (Chron C1n, beginning at 0.781 Ma) to the top of Chron C5n (9.786 Ma).

Using the combination of magnetostratigraphy and biostratigraphic data, we identified three substantial hiatuses or condensed sections. The early Matuyama (much of C2r) and the top of the Gauss (C2An) may be missing or are condensed. Chrons C3n and C4n are completely missing. Similar to Site U1456, there is an "extra" subchron that is not in the official time scale, which is located between the Cobb Mountain (C1r.2n) and the Olduvai (C2n). The identity of this subchron (which could be the Garder [1.472–1.48 Ma] or the Gilsa [1.567–1.575 Ma] according to Channell et al. [2002]) could help constrain the age model during this interval of very rapid sedimentation.

Paleomagnetic data from the bottom-most sediment cores are well behaved, with an average inclination of some 39°. If these are indeed Paleocene in age, they are reversely magnetized and translate to a paleolatitude for the site of approximately 22°S, which is in reasonable agreement with a paleolatitude of between 16°S and 25°S for 60 Ma to 65 Ma (Besse and Courtillot, 2002).

The physical property data collected for Site U1457 includes bulk density, *P*-wave velocity, magnetic susceptibility (MS), and natural gamma radiation (NGR) on whole-round cores from Holes U1457A to U1457C 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, and thermal conductivity generally increase with depth from 1.4 to 3.0 g/cm^3, 1.5 to 5.6 km/s, and 1 to 2.6 W/(m·K), respectively, whereas porosity decreases from nearly 80% to 50% in the upper 100 mbsf, and then to ~20% at the base of Lithologic Unit IV. Shear strength varies between 10 and 70 kPa in the upper 150 mbsf, indicating that the sediment is soft and uncompacted.

Generally the changes in the physical properties are gradual, indicating that sediment compaction plays a significant role in physical property variations. However, shifts in porosity, bulk density, and thermal conductivity are seen between lithologic units, demonstrating the influence that lithology has on physical properties. For example, between Lithologic Units I and II, lithology changes from soft carbonate ooze and clay to detrital silt, clay, and sand, resulting in an increase in bulk density and thermal conductivity, and a decrease in porosity. NGR also increases across this boundary (from ~30 to ~60 cps), whereas magnetic susceptibility becomes less variable and generally lower in Lithologic Unit II compared with Unit I. At the base of Lithologic Unit IV below 1000 mbsf, *P*-wave velocity abruptly increases to values up to 4.3 km/s due to the occurrence of high-density calcarenite and breccia, compared with lower values for the overlying claystone (2.0 km/s). NGR and magnetic susceptibility dramatically decrease over this same interval. A return to lower bulk density (~2 g/cm^3) and *P*-wave (~2.0 km/s) occurs within Lithologic Unit V above the igneous rock at the base of Core 355-U1457-96R. The recovered basalt has characteristically high bulk densities (~2.6 g/cm^3), magnetic susceptibility (~3000 instrumentation units), and *P*-wave velocities (4.5 to 5.5 km/s), but low NGR (~1 cps).

A geothermal gradient of 53°C km^{-1} for the upper ~100 m was estimated from the advanced piston corer temperature tool (APCT-3) measurements taken on Cores 355-U1457A-4H, 7H, and 10H.

Distinctive changes in color, magnetic susceptibility, NGR, and gamma ray attenuation (GRA) bulk density were used to make hole-to-hole correlations between the sediment from Holes U1457A and U1457B. Correlations were limited to these two holes because there was minimal overlap with the cored section of Hole U1457C and there was no opportunity for wireline logging. We constructed a spliced sediment section for Site U1457 from cores recovered from Holes U1457A and U1457B. The splice is good to ~88 m core composite depth below seafloor (CCSF) or about 1.2 Ma. With appended cores, the U1457 splice was extended to 123.55 m CCSF. Profiles in the spliced section of Site U1457 of magnetic susceptibility change (clay content) and color change ($CaCO_3$ variations) are similar to those from Site U1456. Initial age correlations support the hypothesis that the variations can be used to make age correlations between the two sites.

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